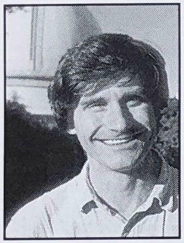

Professor Alex Filippenko is Professor of Astronomy at the University of California at Berkeley. He holds a Ph.D. in astronomy from California Institute of Technology. The most widely cited researcher in Astronomy, he has published over 430 papers. *Science* magazine credited his research team with the "Science Breakthrough of 1998" for research on exploding stars (supernovae). He was voted "Best Professor" by UC Berkeley students in 1995, 2001, 2003, and 2004.

Guidebook Contents

Part 2 of 2

Lecture 9: Einstein's Relativity
Lecture 10: Cosmology and Cosmic Expansion
Lecture 11: The Birth and Evolution of Galaxies
Lecture 12: The Accelerating Expansion of the Universe
Lecture 13: The Stuff of the Cosmos
Lecture 14: Dark Energy—May the Force Be With You
Lecture 15: Theories of Everything, and Hidden Dimensions
Lecture 16: Our Universe, One of Many?

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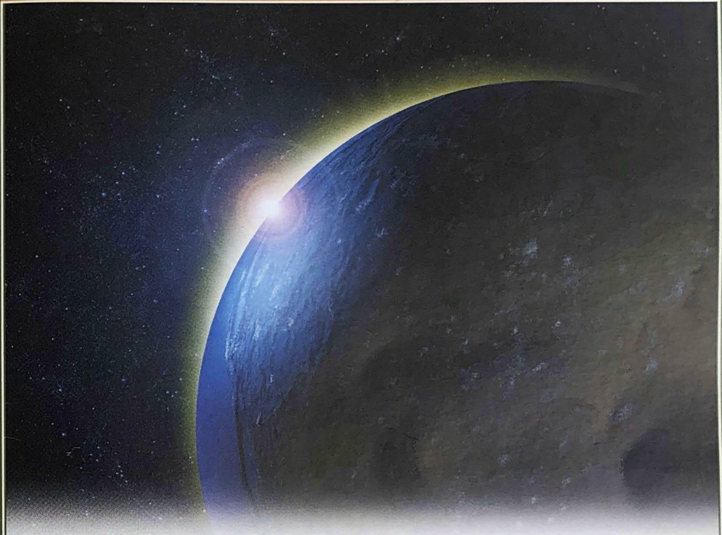

Understanding the Universe:

What's New in Astronomy, 2003

Taught by: Professor Alex Filippenko,
University of California at Berkeley

Part 2

Course Guidebook

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Alex Filippenko, Ph.D.

Professor of Astronomy, University of California, Berkeley

Alex Filippenko received his bachelor's degree in physics (1979) from the University of California, Santa Barbara, and his doctorate in astronomy (1984) from the California Institute of Technology. He subsequently became a Miller Postdoctoral Fellow for Basic Research in Science at the University of California, Berkeley. In 1986, he joined the faculty at UC Berkeley, where he has remained through the present time. A member of the International Astronomical Union, Filippenko has served as President of the Astronomical Society of the Pacific and as Councilor of the American Astronomical Society.

An observational astronomer who makes frequent use of the Hubble Space Telescope and the Keck 10-meter telescopes, Filippenko's primary areas of research are exploding stars (supernovae), active galaxies, black holes, and cosmology. He and his collaborators recognized a new class of exploding star, obtained some of the best evidence for the existence of small black holes in our Milky Way galaxy, and found that other galaxies commonly show vigorous activity in their centers that suggests the presence of supermassive black holes. His robotic telescope at Lick Observatory in California is the world's most successful search engine for nearby supernovae, having discovered more than 300 of them in the past few years. Filippenko also made major contributions to the discovery that the expansion rate of the Universe is speeding up with time (the *accelerating universe*), driven by a mysterious form of dark energy—the top "Science Breakthrough of 1998," according to the editors of *Science* magazine.

Filippenko's research accomplishments, documented in more than 430 published papers, have been recognized with several major awards, including the Newton Lacy Pierce Prize of the American Astronomical Society (1992) and the Robert M. Petrie Prize of the Canadian Astronomical Society (1997). A Fellow of the California Academy of Sciences, Filippenko has also been a Guggenheim Foundation Fellow (2001), a Phi Beta Kappa Visiting Scholar (2002), and a distinguished visiting lecturer at numerous colleges and universities, including the Spitzer Lecturer at Princeton University.

Filippenko has won the coveted Distinguished Teaching Award (1991) and the Donald S. Noyce Prize for Excellence in Undergraduate Teaching in the Physical Sciences (1991), each of which is generally given at most once per career. In 1995, 2001, and 2003, he was voted the "Best Professor" on campus in student polls. Also, in 2002, he won the UC Berkeley Distinguished Research Mentoring of Undergraduates Award. He has delivered hundreds of public lectures on astronomy and has played a prominent role in science newscasts and television documentaries, such as "Mysteries of Deep Space," "Stephen Hawking's Universe," and Nova's "Runaway Universe." With Jay M. Pasachoff, Filippenko coauthored an introductory astronomy textbook, *The*

Cosmos: Astronomy in the New Millennium (2001; 2004, 2nd ed.), which in 2001, won the Texty Excellence Award of the Text and Academic Authors Association for the best new textbook in the physical sciences. In 1998, Filippenko produced a 40-lecture introductory astronomy video course with The Teaching Company, to which the present course is an update.

Table of Contents

Understanding the Universe: What's New in Astronomy, 2003
Part II

Professor Biography i

Course Scope 1

Lecture Nine Einstein's Relativity 3

Lecture Ten Cosmology and Cosmic Expansion 10

Lecture Eleven The Birth and Evolution of Galaxies 17

Lecture Twelve The Accelerating Expansion of the Universe 24

Lecture Thirteen The Stuff of the Cosmos 33

Lecture Fourteen Dark Energy—May the Force Be With You 40

Lecture Fifteen Theories of Everything and Hidden Dimensions 48

Lecture Sixteen Our Universe, One of Many? 56

Glossary ..... Part I

Bibliography 63

Music for this course

written and performed by Matt Venuti and The Venusians: venusians.com

Understanding the Universe: What's New in Astronomy, 2003

Scope:

This visually rich course is designed to provide a nontechnical update to Professor Alex Filippenko's first astronomy course for The Teaching Company, *Understanding the Universe: An Introduction to Astronomy*, which was produced in 1998. Much has happened in the world of astronomy during the past five years, and the primary objective of this course is to discuss some of the more exciting and important advances. Although this course is largely self-contained, you will certainly find it beneficial to view the original introductory course to familiarize yourself with astronomical concepts and to gain sufficient background information that will allow you to more fully understand and enjoy this new set of lectures.

In Part I, the first two lectures are on simple daytime and nighttime observations that you can make to better appreciate the sky and what it contains. Topics include sunspots, partial solar eclipses, the setting Sun and the green flash, Buddha's rays, planets, the Milky Way, constellations, observations with binoculars and small telescopes, northern lights, and more. Lecture Three is devoted to recent advances in our Solar System made with satellites and sophisticated ground-based techniques. One of the most important conclusions, from the discovery of numerous objects near and beyond Pluto's orbit, is that Pluto is not a true planet but, rather, just the largest known member of the Kuiper Belt of icy minor planets. In Lecture Four, we discuss the rapidly moving field of *extrasolar planets*—planets that orbit stars other than the Sun. More than 100 such objects are now known, and we can begin to draw interesting statistical conclusions about them. The formation and evolution of stars is the subject of Lecture Five, a highlight of which is the resolution of the long-standing *solar neutrino problem* and the resulting conclusion that neutrinos have nonzero mass. Moreover, the discovery of large numbers of brown dwarfs, which bridge the gap between giant planets and normal stars, has contributed to an improved appreciation of their true nature.

Lecture Six describes the catastrophic explosions of certain types of stars at the ends of their lives, creating and ejecting into the cosmos the elements of which humans are made. With the discovery and detailed study of many supernovae during the past few years, we now have a much better understanding of stellar explosions and their remnants. Lecture Seven concentrates on the enigmatic *gamma-ray bursts*, whose distances and physical properties were extremely uncertain until recently. We now know that they generally reside in very distant galaxies and, in most cases, are associated with massive stars that collapse or merge to form black holes, high-speed jets of particles, and colossal explosions. Lecture Eight gives strong observational evidence for the existence of black holes, both the stellar-mass variety in binary systems and the supermassive objects in the centers of galaxies. Black holes really do exist! Recently, black holes that are intermediate in mass between the two major known classes appear to have been found.

Lecture Nine, the first lecture of Part II, is devoted to a brief introduction to Einstein's special and general theories of relativity, because their consequences are so abundant among astronomical phenomena. Past and future tests of these theories are described, most notably the search for gravity waves. Cosmology and the expansion of the Universe are the subjects of Lecture Ten. The expansion age of the Universe, 13.7 billion years, has recently been determined with high accuracy, and it slightly exceeds the ages of the oldest known stars; thus, the persistent *age crisis* finally appears to have been resolved. Lecture Eleven discusses the birth and evolution of galaxies, which can be investigated by looking back in time at progressively more distant galaxies. We also consider the *cosmic microwave background radiation*, which predates the light from the first generation of stars and is actually the afterglow of the Big Bang.

The 1998 discovery that the expansion of the Universe is speeding up with time was new and quite uncertain at the time of the 1998 astronomy course, but the evidence is now much better, as discussed in Lecture Twelve. Studies of distant supernovae continue to suggest that there is a dark, repulsive energy pervading space, causing galaxies to recede from each other ever faster. As described in Lecture Thirteen, independent confirmation of this revolutionary conclusion was recently provided by satellite measurements, which showed that the Universe is geometrically flat on large scales and, therefore, must have a substantially higher density than can be explained with visible and dark matter alone. In addition, most of the dark matter must consist of unknown particles that differ from ordinary matter. Given that almost three-quarters of the energy content of the Universe is repulsive *dark energy*, it behooves us to understand its nature; this is the subject of Lecture Fourteen. One possibility is that quantum fluctuations (virtual particles) in the vacuum are the origin of dark energy, but there are problems with this hypothesis. A complete understanding of dark energy probably won't be possible until we have a successful *theory of everything*, unifying quantum physics with general relativity. As discussed in Lecture Fifteen, the most extensive work in this area has been done on *superstring theories*, which postulate that every elementary particle is a different mode of vibration of a tiny energy packet known as a *string*. A strange attribute of such theories is that the Universe contains many hidden dimensions, and physicists are now trying to find experimental evidence for them. In Lecture Sixteen, the course ends by summarizing the way in which an early epoch of exponential expansion can resolve the problems with the standard Big Bang theory. This leads to the notion of multiple universes, possibly having a range of properties—and, naturally, we live in one of the hospitable universes!

Lecture Nine

Einstein's Relativity

Scope: Black holes are well explained with Einstein's theory of relativity, but how do we really know that the theory is correct? How is it tested, and what are its foundations? This lecture briefly describes the special and general theories of relativity, revealing some of the ideas that motivated Einstein to conceive them. The strange consequences of special relativity—time dilation and length contraction—have been abundantly verified in laboratories. The more far-reaching general theory provides an explanation for gravity in terms of the curvature, or warping, of space-time. Tests of the theory include the precession of orbits, the bending of light near the Sun and gravitational lensing, the gravitational redshift, and time dilation. The dragging of space-time around a spinning object, such as the Earth, will soon be definitively measured with a new satellite. A major prediction of general relativity is that gravity waves (ripples in the fabric of space) are produced when celestial objects merge. Several ambitious instruments have been built or are being planned to detect gravity waves from coalescing neutron stars and black holes.

Outline

I. Albert Einstein's special and general theories of relativity are masterpieces of creative thought, and examples of their consequences abound in the cosmos, as well as in everyday life.

A. One of the most amazing predictions is the existence of black holes. As described in the previous lecture, we now have excellent observational evidence for these objects.

B. But how do we know their size, aside from simply believing the prediction of relativity?

1. The *event horizon* of a black hole is the region from within which nothing can escape; it's essentially the point of no return.
2. Its radius, the *Schwarzschild radius*, is given by $R = 2GM/c^2$, where M is the black hole's mass, G is Newton's constant of universal gravitation, and c is the speed of light.
3. For a black hole of 10 solar masses, $R = 30$ km—far too small to directly see in stellar-mass black holes in X-ray binary systems that are many light years away.
4. Even for a 10-million solar mass black hole, $R = 30$ million km, which is only about 1/5 of the distance between the Earth and Sun (that is, 1/5 of an astronomical unit). This is much too small to see in the middle of any galaxy, including our own.

C. How do we know, then, that the numerical predictions of relativity are right? Are there other tests of relativity that can give us enough confidence to use it?

D. How do we know that the strange consequences and predictions of relativity are true?

E. Moreover, what are the foundations of relativity? What motivated Einstein to come up with such a counterintuitive-sounding theory in the first place?

F. Einstein's work is so important and influential that he was chosen as the "Person of the 20th Century" by the editors of *Time* magazine.

  1. An obvious example of relativity is $E = mc^2$, the single most recognized physics equation in the world (and the basis of nuclear energy and nuclear bombs).

  2. Given that relativity affects us in numerous and profound ways, and concepts from relativity come up many times in this course about the cosmos, we should take time to understand its foundations.

II. The *special theory of relativity* deals with constant speeds and ignores gravity.

A. In the early 20th century, it was known that Maxwell's equations of electromagnetism and Newton's formulation of mechanics (which was based on Galileo's observations) were incompatible.

  1. For example, in Maxwell's equations, the speed of light, c, is independent of the motion of the source or the observer.

  2. This is contrary to the usual way in which we add or subtract speeds, such as when we are riding in cars.

  3. There was actually some evidence (the Michelsen-Morley experiment) for the constancy of the speed of light, but Einstein apparently was not aware of it.

B. Einstein felt that the equations of electromagnetism are so beautiful that they must be correct; thus, he decided that the flaw was in Newtonian/Galilean mechanics.

C. He made two assumptions whose consequences completely changed our view of space and time.

  1. First, the *principle of relativity*: The laws of physics are the same for all observers moving at constant speed and direction relative to each other. This seems reasonable. After all, you don't play ping-pong any differently on a yacht.

  2. Second, the speed of light is the same for all observers, regardless of their motion relative to the source of light.

D. It is easy to show that at least four major consequences follow directly from these assumptions.

  1. Time dilation: Let an event occur over a given time interval t_0 according to an observer in a stationary frame of reference. According to an observer watching that frame moving with speed v relative to himself, the event will take a *longer* time interval $t_1 = t_0/[1 - (v/c)^2]^{1/2} = \gamma t_0$, where $\gamma = 1/[1 - (v/c)^2]^{1/2}$.

  2. Length contraction along the direction of motion: Let an object have length l_0 according to an observer in a stationary frame of reference. According to an observer watching that frame moving with speed v relative to himself, the length will be *shorter*: $l_1 = l_0/\gamma$.

  3. Events that are simultaneous in one frame of reference will generally not be simultaneous in another frame moving relative to it.

  4. $E = mc^2 = \gamma m_0c^2$. In words, an object with rest-mass m_0 moving at speed v is equivalent to an amount of energy E; if $v = 0$, then $E = m_0c^2$.

E. The function γ has interesting properties. It hardly differs from 1.0 for speeds up to a few tenths of c, but rapidly approaches infinity as v approaches c.

  1. For example, $\gamma = 1.155, 2.294, 7.089, 22.37$, and 70.7 at (respectively) $v/c = 0.5, 0.9, 0.99, 0.999$, and 0.9999.

  2. Given that $E = \gamma m_0c^2$ and $m_0 > 0$ for any material particle, we immediately see why it is impossible for such a particle to reach the speed of light, $v = c$, while moving through space: It would take an infinite amount of energy to do so!

  3. Thus, special relativity forbids the transmission of information through space at speeds exceeding c.

F. An illuminating example of time dilation, length contraction, and the essence of relativity is the case of a muon (a short-lived particle) emitted by a source at one end of a lab and detected at the other end of the lab.

  1. The muon and the lab observer agree on the experimentally verifiable facts: Muons are created at one end of the lab and detected at the other end of the lab.

  2. They disagree about *how* it happened—yet this is not measurable.

  3. Each of them is completely correct, from its frame of reference.

  4. This is the essence of relativity! Time and space depend on one's state of motion.

G. The predictions of special relativity have been tested so thoroughly by experiments such as the one above that the theory is now essentially beyond doubt. Indeed, even some familiar items, such as TV sets, wouldn't work if the effects of special relativity didn't exist.

III. Now let's consider Einstein's *general theory of relativity*.

- **A.** Newton assumed that his law of universal gravitation, $F = Gm_1m_2/d^2$, utilizes instantaneous "action at a distance."
  - **1.** For example, if the Sun's mass were to suddenly disappear from the Universe, Newton's law implies that the force between the Sun and the Earth would instantly be cut off. The Earth would immediately go flying off along its instantaneous direction of motion (that is, along a tangent) at the moment the Sun disappeared.
  - **2.** But Einstein's special theory of relativity forbids information from traveling through space faster than the speed of light, let alone instantaneously.
    - **a.** Newton's theory was clearly "broken," and its repair required an understanding of how it works.
    - **b.** But by his own admission, Newton did not know the *mechanism* of gravitation.
- **B.** Einstein decided to start with a clean slate; he considered gravity from an entirely different perspective.
  - **1.** His key idea was that acceleration and gravity are profoundly interwoven.
  - **2.** This is succinctly expressed as the Principle of Equivalence (1907): There is no difference between the laws of physics in a uniform gravitational field and in a uniformly accelerated frame of reference.
  - **3.** For example, if you are standing in a windowless elevator and it suddenly accelerates up, you feel heavier, but unless the door opens and you find yourself on another floor, an equally valid possibility is that a large mass was temporarily placed beneath the elevator, increasing the gravitational field there.
  - **4.** Einstein's famous elevator thought experiment easily shows that light should be bent in a gravitational field.
    - **a.** An observer in an elevator moving with a constant speed would see light travel in a straight line, because that is what happens in elevators at rest.
    - **b.** However, an observer in an elevator accelerating upward would see light travel in a path that curves downward, because the light cannot "know" that the elevator is accelerating.
    - **c.** Since accelerations and gravitational fields are equivalent, light must also bend in a gravitational field!
- **C.** As Einstein further formulated general relativity, he found that the paths of light and particles in a gravitational field can be represented by their natural paths in curved space-time. A well known analogy is a ball moving along a warped rubber sheet.

  - **1.** Mass or energy produces space-time curvature: Distances and times are warped (altered), analogous to special relativity.
  - **2.** Conversely, space-time curvature can be thought of as mass (or energy).
- **D.** Many examples of general relativistic effects have already been tested.
  - **1.** Light bends as it passes through gravitational fields, such as near the Sun (where the effect was first seen) or a cluster of galaxies (where we have seen gravitational lensing effects).
  - **2.** The orbits of objects are not closed ellipses; rather, they shift (*precess*) with time, with the rate of shift increasing in stronger gravitational fields. This was first seen with the orbit of Mercury.
  - **3.** Light emerging from a gravitational field is redshifted as the photons lose energy. This has been seen even in weak fields, such as that of the Earth.
  - **4.** Time slows down in a gravitational field, as seen by an observer outside that field. Near a black hole, the effect can be extreme: One can age much less than observers on Earth. But the effect has been measured with atomic clocks even in Earth's gravitational field.
  - **5.** The most precise tests of general relativity have been made with a specific *binary pulsar*: a system of two neutron stars (one visible as a pulsar) orbiting each other with a period of only about 8 hours.
    - **a.** The pulsar's orbit is precessing, much more than that of Mercury around the Sun.
    - **b.** The orbital period is decreasing as the two stars gradually spiral toward each other.
    - **c.** Presumably, the system is losing energy through the emission of *gravity waves*, which are "ripples" in the fabric of space-time that move at the speed of light.
    - **d.** The rate of emission of gravity waves should increase as the orbital separation decreases, and it will be highest when the stars are merging.

IV. Although the existence of gravity waves is predicted by general relativity, we have not yet *directly* detected the gravity waves themselves. They are incredibly weak and hard to detect.

- **A.** A gravity wave passing through an object (or even through empty space) has a distinctive signature.
  - **1.** First, the wave stretches the object along one axis and squeezes it along the other axis.
  - **2.** Then, the wave squeezes the object along the first axis and stretches it along the second.

3. The amount of stretching and squeezing is minuscule, however: For a bar 1 meter in length, the difference in length is about one-millionth of the diameter of a proton!
4. Joseph Weber was a pioneer in the development of gravity-wave detectors, but the measurement was simply too difficult to make with the available equipment.

B. Thus, to attempt the detection of gravity waves from merging neutron stars, physicists have built large, evacuated, L-shaped tubes through which laser beams pass. Such a device is known as LIGO (Laser Interferometer Gravitational-wave Observatory).

1. The laser beams are used to measure the distance between mirrors mounted on hanging masses at the ends of the tubes and at their intersection point.
2. If a gravity wave passes through, the space in one tube should contract while that in the other expands, and analysis of the laser beams will reveal this if the effect is sufficiently large.
3. To guard against "false positives" (that is, incorrect conclusions), two facilities have been built in the United States (one near Hanford, Washington, and the other near Livingston, Louisiana). Both of them have to detect the gravity wave in order for the result to merit interest.
4. LIGO has not yet detected any gravity waves, and perhaps it never will. However, it is an important step in the development of future, better instruments.

C. The most well known project being planned is LISA—the Laser Interferometer Space Antenna.

1. After being launched, it should be able to detect gravity waves from various sources.
2. Its detectors will be separated by 5 million km, not just 4 km, as in LIGO.

D. Another test of general relativity is known as the *dragging of inertial frames*.

1. Space-time near a rotating object is partly dragged along with it.
2. Some aspects of the X-ray emission from the accretion disk around a few stellar-mass black holes suggest frame dragging, but the evidence is not yet convincing.
3. A very sophisticated space experiment, Gravity Probe B, will soon be launched to look for direct evidence of frame dragging around the rotating Earth.
    - **a.** The effect is tiny: only 0.042 seconds of arc per year.
    - **b.** To determine the orientation of the gyroscope in Gravity Probe B, its magnetic field orientation will be measured with a complex device.

E. Confirmation of the existence of gravity waves and frame dragging, together with all the other existing tests, would demonstrate that general relativity is correct in essentially all its details.

Essential Reading:

Mook and Vargish, *Inside Relativity*.

Wolfson, *Simply Einstein: Relativity Demystified*.

Supplementary Reading:

Hawking, *The Universe in a Nutshell*.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy*.

Questions to Consider:

1. Suppose a muon is emitted from one end of a laboratory that is 1 km long. It lives for only 1 microsecond (1 millionth of a second) in its own frame of reference and travels through the lab at 99% the speed of light. Show that according to Newtonian physics, it cannot reach the other end of the lab before dying. Quantitatively demonstrate how special relativity resolves the discrepancy from both the muon's perspective and the lab observer's perspective.
2. Argue how you could travel close to the speed of light or hover near the event horizon of a black hole, if you wanted to jump into the future without aging much. But would your actual lifetime (as measured, say, but the number of books you read) be any longer in your own frame of reference? Also, could you subsequently go back in time to report your observations of the future to your old friends and family?

Lecture Ten

Cosmology and Cosmic Expansion

Scope: What is the overall shape and fate of the Universe? When was it born? How are such galaxies as the Milky Way born, and how do they change with time? We can address these questions in part by looking back in time: We see distant objects in the Universe as they were long ago, when the light left them, because light travels at a finite speed. The redshifts of galaxies suggest that the Universe is expanding. Expansion makes sense even if the Universe's extent is infinite: The Universe simply becomes less dense. The current expansion rate has been determined quite well from measurements of the distances and redshifts of relatively nearby galaxies. Type Ia supernovae have provided the most accurate distances of galaxies, through the inverse-square law of light. Extrapolating the expansion backward in time, we find that the Universe came into existence (through the *Big Bang*) about 14 billion years ago. This value is consistent with the age of the oldest known stars, about 13 billion years, and with an independently determined age from the recent WMAP satellite.

Outline

I. Cosmology is the study of the birth, structure, and evolution of the Universe as a whole.

- **A.** We are all interested in the age of the Universe, its overall size and shape, and its ultimate fate.
- **B.** We are also interested in how galaxies such as ours formed and evolved.
  - **1.** Galaxies are the basic building blocks of the Universe.
  - **2.** The northern Hubble Deep Field was captured using the Hubble Space Telescope over the course of 10 consecutive days in December 1995.
  - **3.** The telescope was pointed to a spot in the sky near the Big Dipper.
  - **4.** This picture covers a tiny fraction of the sky, comparable to the size of a grain of sand held at arm's length.
  - **5.** Yet, in this tiny region, there are about 1000 galaxies.
- **C.** Another very deep exposure, but in the southern skies (the Hubble Deep Field—South), was obtained in 1997, and it shows a comparable number of galaxies in only a tiny fraction of the sky.
  - **1.** Thus, the Hubble Deep Field—North was a typical part of the sky.
  - **2.** Extrapolated over the whole sky, there are 50 to 100 billion galaxies in the parts of the Universe we can see (only a small fraction of the entire Universe!).
  - **3.** How did these galaxies form and evolve? These are among the questions of modern cosmology.

II. As discussed extensively in *Understanding the Universe*, 1998, the Universe is expanding.

- **A.** In 1929, Edwin Hubble discovered that the more distant a galaxy, the greater is the redshift of its spectrum.
- **B.** If interpreted as a speed according to the Doppler effect, larger redshifts correspond to faster speeds of recession; the Universe of galaxies is expanding.
  - **1.** However, the redshift is actually produced by the expansion of space itself, *not* by the motion of galaxies through a preexisting space.
  - **2.** At low speeds, the formula for speed is the same as that given by Doppler—but the deeper meaning of the redshift is obscured by the Doppler interpretation.
- **C.** The Hubble diagram, a plot of distance (generally along the x-axis, using Edwin Hubble's convention) vs. the speed of recession (generally along the y-axis), reveals a straight line; Hubble's law: $v = H_0 d$, where H_0 (pronounced "H-nought") is the present value of *Hubble's constant* (a constant in space, not time).
- **D.** Note that the galaxies themselves are not expanding; they are gravitationally bound strongly enough to overcome the natural tendency of space to expand.
  - **1.** Similarly, stars and planets are not expanding; they, too, are held together by gravity.
  - **2.** Even most clusters of galaxies are sufficiently strongly bound (by gravity) to resist the expansion.
  - **3.** People and other objects on Earth are not expanding either; they are held together by electromagnetic forces.
  - **4.** Only the space between clusters of galaxies spreads.
- **E.** What evidence do we have that the redshift is produced by expansion, rather than by some other process, such as light getting "tired" and losing energy (and, hence, shifting to longer wavelengths) as it traverses huge distances across the Universe?
  - **1.** Type Ia supernovae are seen at very large distances, and their light curves (brightness vs. time) show a *slower* rise to maximum brightness and a slower decline, as well.
    - **a.** This is exactly what is expected if space is expanding.
    - **b.** It takes photons progressively more time to reach us as the distance between us and the supernova increases.
  - **2.** Also, the *surface brightness* (brightness per unit area) of distant galaxies decreases with distance in a way that is consistent with the expansion of space being the cause of the redshifts.

III. In some ways, the expansion of the Universe is similar to a colossal explosion.

- **A.** For example, if you kick a pile of tennis balls, some of the balls are given a lot of energy, and others are given less energy.
  - **1.** Those that were kicked hardest travel the fastest; those that were kicked very little travel slowly.
  - **2.** After a while, we see that the balls farthest from the center are traveling fastest. To have reached the farthest distance in a given time, they had to be traveling faster than other balls, because they all started in the same place.
- **B.** However, the explosion analogy for the Universe fails in at least one important respect: An explosion has a unique center, but the expansion of the Universe has no unique center, at least not in any physically accessible dimension.
  - **1.** There is observational evidence that we are not the center.
    - **a.** If the expansion of the Universe were like the explosion of a bomb, with us at the center, we would expect the number of galaxies per unit volume to decrease with increasing distance.
    - **b.** But galaxies are *not* observed to thin out at large distances—providing direct evidence that we are not at the unique center.
  - **2.** Thus, the birth of the Universe—the Big Bang—was not an explosion within a preexisting space.
    - **a.** Rather it was the beginning of the expansion of space itself—expansion that continues to this very day.
    - **b.** No matter which galaxy we are in, we would see essentially all other galaxies (except those gravitationally bound to us in the same cluster) receding from us.
    - **c.** For example, if one stretches a rubber tube with ping-pong balls on it, all of them recede from each other; it doesn't matter which ball we choose to be on.
- **C.** A three-dimensional analogy is an expanding loaf of raisin bread.
  - **1.** Because the yeast is uniformly spread throughout the dough, the dough expands uniformly.
  - **2.** The raisins are the galaxies, or clusters of galaxies, that do not spread.
  - **3.** No matter which raisin you are on, the others recede from you; there is no unique center.
  - **4.** At any given time, the more distant raisins recede faster than nearby raisins, simply because there is more expanding dough between distant raisins.
  - **5.** The raisin bread must be infinite to improve the analogy with the real Universe, which has no edge. Or, you can imagine the dough wrapping around so that there is no edge.

- **D.** To see what is meant by "wrapping around," consider a two-dimensional analog: an expanding spherical balloon, with stickers stuck to it.
  - **1.** Let this hypothetical two-dimensional universe be only the rubber itself: you can go forward and backward, left and right, or any combination of those two motions.
  - **2.** You cannot, however, go inside or outside the balloon ("up and down")—that is a mathematically conceivable but physically unreachable dimension.
  - **3.** As I blow into the balloon, the stickers recede from each other and follow Hubble's law, but none can claim to be the unique center.
- **E.** How can the Universe possibly be expanding if it is already infinite?
  - **1.** There is no real difficulty here, because the density of the Universe is decreasing, and this is a measure of the expansion.
  - **2.** For a helpful analogy, consider the counting numbers: 1, 2, 3, 4, 5, 6,….
    - **a.** Now consider just the even numbers: 2, 4, 6, 8, 10, 12,….
    - **b.** The even numbers constitute a set that is mathematically the same size as the counting numbers (it is infinite), but clearly, some of the numbers (the odd ones) are missing—it is, in a sense, less dense than the set of counting numbers.
    - **c.** In a similar manner, it makes sense to study an expanding universe whose density decreases with time, even if that universe is infinite.
- **F.** If you found the above analogy unsatisfactory, because it makes "infinity" sound strange, consider an extension of it that may be more helpful—even though it will make infinity sound even more bizarre!
  - **1.** Between 0 and 1, there are an infinite number of rationals—numbers that can be expressed as fractions, such as 3/5.
  - **2.** However, strange as it may seem, that set of rationals is mathematically the same size as the counting numbers 1, 2, 3, 4,….
  - **3.** The same can be said for any two arbitrarily closely spaced fractions, such as 1/6 and 1/5: There is an infinite number of rationals between them.
  - **4.** Yet, the sum of *all* of the above sets of rationals (between 0 and 1, 1 and 2, 2 and 3, 1/6 and 1/5, and so on) is still exactly the same mathematical size as the counting numbers!
    - **a.** This can be proved by outlining a counting scheme that won't miss *any* of the rational numbers.
    - **b.** Thus, the set of rational numbers is countably infinite, yet it is clearly "denser" than the set of counting numbers.
    - **c.** Compared with this, the expansion of an infinite universe should be easy for you to accept!

G. It is important to emphasize that Hubble's law, in and of itself, does *not* imply that the speed of a given galaxy increases with time.

  1. Hubble's law implies that at a *given time*, distant galaxies are receding from us faster than nearby galaxies.

  2. The speed of a *given* galaxy at best remains constant with time.

  3. In fact, the speed *should* even decrease with time, because of the attractive gravitational pull between galaxies. (But there will be an interesting twist to this in Lecture Twelve!)

  4. Hubble's constant is a constant throughout the Universe at a given time.

IV. There have been many attempts to measure the present value of Hubble's constant, H_0.

A. We need the distance and recession speed of many galaxies. Then, we compute the average value of $H_0 = v/d$.

  1. The recession speeds are easy to get from the measured redshifts of galaxies.

  2. Distances are harder to determine.

B. Being so powerful, Type Ia supernovae can be used to determine the distances of distant galaxies using the inverse-square law of light.

  1. Type Ia supernovae all have nearly the same peak luminosity (power).

  2. Thus, by measuring the apparent brightness *(b)* of a Type Ia supernova in a galaxy and knowing its intrinsic luminosity *(L)*, we can determine its distance *(d)* from the inverse-square law, $b = L/(4\pi d^2)$.

  3. However, they are not all exactly the same: Measurements of Type Ia supernovae in galaxies of known distance have shown that there is a scatter of about 50% in their peak luminosity, *L*. This scatter, if left unresolved, would compromise the utility of Type Ia supernovae for cosmology.

C. Fortunately, our detailed studies of nearby Type Ia supernovae have shown that the more luminous ones have slower light curves (that is, they rise and decline more slowly) than the less luminous ones.

  1. After being calibrated with nearby Type Ia supernovae, this trend allows us to effectively "read the label on the light bulb" when using distant Type Ia supernovae to determine distances.

  2. Suppose you measure the peak brightness of a Type Ia supernova. Rather than assuming that its luminosity is the standard amount, you can measure the light curve and determine whether it is a normal Type Ia supernova, a subluminous one, or an overluminous one.

  3. For example, instead of assuming that $L = 100 \pm 50$ watts, you can conclude that the object has $L = 87 \pm 15$ watts, leading to a more accurate and precise distance determination.

D. After properly calculating the distance of a galaxy containing a Type Ia supernova, we can plot its distance and recession speed on the Hubble diagram.

  1. Doing this for a bunch of galaxies allows us to determine the slope, which is the Hubble constant.

  2. The accuracy of the technique, however, had been limited in its early years because the absolute peak luminosity of Type Ia supernovae was not known.

E. The most comprehensive attempt to determine distances of relatively nearby galaxies, including ones in which Type Ia supernovae had been found, was the Hubble Space Telescope Key Project to measure the apparent brightness of Cepheid variable stars in these galaxies.

  1. As discussed in *Understanding the Universe*, 1998, Cepheids are quite luminous and have well-measured properties; thus, they are excellent cosmological tools.

  2. The final value published by the Key Project team, in the late 1990s, was $H_0 = 72 \pm 7$ km/s/Mpc.

    a. This means that a galaxy 10 Mpc away (about 32.6 million light years away, because 1 parsec = 3.26 light years) recedes from us with a present speed of 720 km/s.

    b. Similarly, a galaxy 20 Mpc away recedes from us with a present speed of 1440 km/s.

F. A more recent measurement provided by another technique, measurement of the cosmic microwave background radiation (to be described in Lecture Thirteen), gives a very similar value, $H_0 = 71 \pm 4$ km/s/Mpc.

G. For the remainder of these lectures, we will adopt $H_0 = 71 \pm 4$ km/s/Mpc, different from (but consistent with, given the stated uncertainties) the value of 65 ± 7 km/s/Mpc used in *Understanding the Universe*, 1998.

V. From the present value of the Hubble constant and knowledge of the past history of the expansion rate (to be discussed in Lecture Twelve), we can determine the expansion age of the Universe.

A. This turns out to be 13.5 to 14 billion years; 13.7 is the formal answer.

B. It is higher than the expansion age computed in the mid-1990s, which was 8 to 12 billion years.

  1. At that time, the age of the oldest known stars, in globular star clusters, was thought to be significantly greater: 14 to 17 billion years.

  2. Hence, there was an *age crisis*.

C. The newly determined expansion age of the Universe is now consistent with the age of the oldest stars, which has been revised down to about 13 billion years.

1. The age of the oldest stars in globular clusters was deduced by examining which kinds of stars have, and which kinds have not yet, burned out (used up the hydrogen in their cores).
    a. This age turns out to be about 13 billion years.
    b. It didn't take long for these stars to appear after the Big Bang; thus, 14 billion years is a reasonable approximation to the age of the Universe.
2. Moreover, an independent determination was made from the observed temperature and brightness of the dimmest white dwarf stars in globular clusters.
    a. The oldest white dwarfs turn out to be 12.7 billion years old.
    b. Adding about 1 billion years for the formation and normal evolution of the (relatively massive) stars up to the white dwarf stage, we get a total of about 13.7 billion years for the age of the Universe.

D. It is very satisfying that the age crisis appears to have finally been resolved.

Essential Reading:

Hogan, *The Little Book of the Big Bang: A Cosmic Primer*.

Kirshner, *The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos*.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Supplementary Reading:

Ferguson, *Measuring the Universe*.

Ferris, *The Whole Shebang: A State of the Universe(s) Report*.

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Questions to Consider:

1. What is the distance of a galaxy having a redshift $z = 0.1$, if Hubble's constant is 71 km/s/Mpc. (Recall that for relatively low redshifts, $z \approx v/c$.)
2. Why do you think very nearby galaxies, such as the Andromeda galaxy (M31), can give erroneous values for the Hubble constant?

Lecture Eleven

The Birth and Evolution of Galaxies

Scope: The Hubble Space Telescope has provided amazing views of galaxies at progressively greater distances, up to about 13 billion light years away, allowing us to study how galaxies evolve with time. Gravitational lensing of very distant galaxies by clusters of galaxies along the line of sight allows us to study their magnified light. There used to be an enormous number of rather small galaxies, but they gradually merged to form larger ones. The merging process leads to rampant star formation, sometimes in the form of massive star clusters. The Big Bang theory suggests that the early Universe was hot and dense, and we now see the remaining radiation from this stage: the cosmic microwave background radiation, which was released at an age of 380,000 years when protons and electrons combined to form neutral atoms. Evidence indicates that the microwave background must be the afterglow of the Big Bang. The recent WMAP satellite suggests that the first generation of stars was born about 200 million years after the Big Bang. These stars, as well as quasars powered by supermassive black holes swallowing nearby material, emitted so much light that the Universe emerged from its *dark ages*.

Outline

I. The Universe is expanding, and it has been doing so for the past 13.5 to 14 billion years, since its birth.

A. As discussed in Lecture Ten, the derived expansion age is consistent with the ages of the oldest stars.

1. Recent measurements with a new satellite, the Wilkinson Microwave Anisotropy Probe (WMAP), pinpoint the age at 13.7 ± 0.2 billion years.
2. This means that if we could look back in time, the farthest back we could possibly see is 13.7 billion years.

B. The redshifts of galaxies tell us how much the Universe has expanded since the time when the light we are now seeing was emitted by the galaxy.

1. The redshift is related to the distance of an object, but "distance" is a somewhat ambiguous term at high redshifts.
    a. Given that space expanded while the light was on its way to us, does the derived "distance" correspond to the distance at which the object emitted the light?
    b. Does it instead correspond to the object's distance right now?
    c. In fact, it corresponds to some intermediate value, but this is cumbersome.

2. For large redshifts, it makes more sense to talk about the *lookback time*, rather than the distance.
    a. The lookback time is the amount of time elapsed between the emission and detection of the light from the object.
    b. The lookback time tells us how far back into the past we are looking when we view an object at a given redshift.
3. One can make a table of redshift vs. lookback time, assuming $H_0 =$ 71 km/s/Mpc and an expansion history of the Universe (to be discussed in Lecture Twelve).
    a. For example, redshifts of 0.1 and 0.2 correspond to lookback times of 1.3 and 2.4 billion years, respectively.
    b. Redshifts of 6.0 and 7.0 correspond to lookback times of 12.7 and 12.9 billion years, respectively.

II. The Hubble Space Telescope has provided amazing views of galaxies at progressively greater lookback times, allowing us to study how galaxies evolve with time.

A. Thus, we are effectively seeing a *movie* of the evolution of the Universe.
1. We assume that typical galaxies back then and over there evolved into typical galaxies here and now.
2. Galaxies at the highest known redshifts, between 6 and 7, are seen as they were when the Universe was only about a billion years old.

B. But very distant galaxies are hard to study, because even the Hubble Space Telescope images don't have enough clarity to show fine details.
1. NASA is planning to build a larger successor to the Hubble Space Telescope, the James Webb Space Telescope. The expected completion date is 2010.
2. It will be able to provide even better images of high-redshift galaxies.

C. Some aspects of very high-redshift galaxies have been studied in greater detail than expected because foreground clusters of galaxies have gravitationally lensed their light.
1. This makes them appear much brighter. We are essentially using the cluster of galaxies as a telescope focusing the light!
2. The shapes of the distant galaxies are distorted into arcs and are not reliable indicators of their true shapes.
3. However, the redshifts and types of stars (young, old, and so on) in the galaxies are easier to study (with spectra) because the galaxies are brighter than would have been the case without the gravitational lensing.

D. Large galaxies appear to have grown through a process of repeated merging.

1. There used to be a far larger number of small, blue, irregular galaxies. These were probably experiencing one of their first bursts of star formation.
2. Many of these "galaxy building blocks" merged together to form larger galaxies.
3. Most spiral galaxies used to look quite peculiar, probably because of mergers. There were few large, well-formed spiral arms in the past.
4. When galaxies merge, or even when they experience close gravitational interactions, intense bursts of star formation are induced. *Super star clusters*, consisting of very large numbers of stars, are formed.
5. Examples of such star clusters are found at low redshifts, too, in strongly interacting or merging galaxies.
6. Some of the merging galaxies produce copious amounts of dust that obscures the newly formed stars at optical wavelengths. These objects glow brightly at infrared wavelengths.

E. Distant galaxies can be found by taking photographs of the same regions of the sky through ultraviolet, green, and red filters.
1. Distant galaxies are generally bright in the red and green filters, but faint or invisible in the UV filter.
    a. The expansion of space stretches the UV light to longer wavelengths.
    b. Also, intervening clouds of gas absorb the UV light.
    c. At still higher redshifts, the galaxies may be visible only through the red filter.
2. Studies of galaxies at a wide range of redshifts have provided the history of star birth in the Universe.
    a. The highest rate of star formation was in the first 0.5 to 1 billion years after the Big Bang, subsequently tapering off.
    b. This differs from the old model of the star birth rate, which had it peaking at an age of about 5 billion years.

F. The merging process also led to the formation of temporary *tidal tails* as stars and gas were ripped away from the galaxies.
1. Computer simulations of merging galaxies yield models that appear strikingly similar to observed objects.
2. Two large, merging spiral galaxies look very complex and distorted for a while, but they can eventually form an elliptical galaxy.
    a. Most elliptical galaxies seem to have formed very early in the Universe.
    b. Some formed later, from the merging of two spiral galaxies.
3. Milky Way galaxy and the Andromeda galaxy, now only 2.4 million light years apart, are approaching each other and will

collide in 5 or 6 billion years. Subsequently, they will merge and probably become an elliptical galaxy.

4. Other, smaller galaxies in our Local Group of galaxies will also merge.

a. Eventually, our Local Group will become just one gigantic galaxy.

b. This process can be thought of as *galactic cannibalism*.

G. But how and when did the first little galaxies form? What was the Universe like *before* the first stars and galaxies formed?

1. Because there was no light from stars and galaxies, we call that time the *dark ages*.

2. To study the dark ages, we must go back to even earlier times.

III. The early Universe was opaque to electromagnetic radiation, well before stars and galaxies formed.

A. The afterglow of the Big Bang is now detected as the famous cosmic microwave background radiation (CMBR) that pervades the Universe.

1. Arno Penzias and Robert Wilson discovered the CMBR with a Bell Labs radio telescope in the mid-1960s.

2. They didn't know what they had found, but they were very careful researchers who refused to ignore the slight "noise" in their measurements of the sky.

3. You can detect the CMBR on your television set if you go to a channel that has no local station. A few percent of the noise spikes that you see are due to CMBR photons!

B. Early in its history, the Universe was so hot that electrons were not bound to atomic nuclei but, rather, were free to bounce around among all their neighbors.

1. The Universe was ionized at this time.

2. It was a dense plasma consisting of electrons and atomic nuclei (mostly hydrogen and helium).

3. Photons (electromagnetic radiation) could not travel very far without scattering off an electron and changing directions; the Universe was not transparent.

4. Even if there had been discrete objects at this time, one would not be able to see them because the Universe was opaque.

C. However, 380,000 years after the Big Bang, the temperature of the Universe had cooled to about 3000 K because of the expansion of the Universe.

1. Electrons then combined with protons to form neutral hydrogen atoms—a process called *recombination*, even though this was the *first* time that electrons were combining with protons in the history of the Universe.

2. Photons (electromagnetic radiation) scattered off free electrons for the last time just before recombination. Thereafter, they were able to travel freely through the Universe. Most of them didn't have the right energies (wavelengths) to be absorbed by the hydrogen atoms.

3. The Universe, therefore, became transparent to most wavelengths of electromagnetic radiation, specifically the optical (visible) light that was then dominant.

4. By now, cosmic expansion has stretched the CMBR from optical wavelengths to microwaves (radio waves), corresponding to a universe whose average temperature is only about 2.7 K (that is, 2.7 degrees above absolute zero).

5. George Gamow and his associates predicted the existence of the CMBR in 1948. However, their prediction was largely ignored; it seemed to be too far ahead of its time.

D. The CMBR was actually detected in 1940 and subsequently, but it was not recognized as the afterglow of the Big Bang.

1. Studies of absorption lines produced by cyanogen molecules (CN) in clouds of gas show that the molecules must have been bathed in radiation having a characteristic temperature of about 2.7 K. They are in excited states that are populated by such radiation.

2. Evidence that the CMBR corresponded to a higher temperature in the past is found from studies of high-redshift CN (cyanogen) molecules: More of them are in the excited states.

E. We can tell that the CMBR was produced at very large distances, because as it travels through clusters of galaxies on its way toward us, we see that some of the photons get scattered to larger energies.

1. This is known as the *sunyaev-Zel'dovich effect*, after two Russian astrophysicists who predicted it.

2. If the CMBR were formed close to us and was not evidence of a hot beginning for the Universe, there would be no correlation between its spectrum and the presence of distant clusters of galaxies.

IV. At some time after the Universe released the cosmic background radiation (that is, after $t = 380{,}000$ years), the first stars and galaxies, or building blocks of galaxies, must have started forming out of density variations in the early Universe.

A. But when and how did they form? We can answer this question by looking very deeply in the Universe, searching for the highest redshift objects.

1. For example, the most distant known galaxy has a confirmed redshift of $z = 6.6$.

a. It formed only a billion years after the birth of the Universe.

- **b.** Other faint galaxies that are probably at comparable distances have been found, but their redshifts have not yet been determined.

2. Even more remarkable is the discovery of a luminous quasar at redshift 6.4, by the Sloan Digital Sky Survey that was conducted at optical wavelengths.

- **a.** Many other high-redshift quasars have been found in various surveys, including deep images made by the Chandra X-ray Observatory.
- **b.** The huge power of these quasars can be explained only if large amounts of matter are being swallowed by a supermassive black hole at the center of each quasar.
- **c.** But supermassive black holes are difficult to form in such a short time, only 1 billion years after the Big Bang.
- **d.** Large quantities of *dark matter* must have existed early in the Universe, to help form these black holes so rapidly.

B. The earliest stars were probably more massive than typical stars today. The formation of low-mass stars requires gas to cool substantially, and this was difficult for gas to do when it consisted entirely of hydrogen and helium, with no heavy elements.

1. The massive stars, as well as quasars, emitted great quantities of ultraviolet radiation.
2. These massive stars had short lives and soon exploded as supernovae, contributing even more starlight to the young Universe.
3. During the first 0.5 to 1 billion years of the Universe, the star-formation rate was very high, and it tapered off since then.

C. The large amounts of ultraviolet radiation must have *ionized* the Universe at some time after $t = 380{,}000$ years.

1. The free electrons from this process of *reionization* would not be dense enough to affect the CMBR or other photons very much, because they were produced after the Universe had expanded by a large factor.
2. Very recent data from the WMAP satellite suggest that reionization started to occur about 200 million years after the Big Bang.
3. Thus, the dark ages were between $t = 380{,}000$ years and about 200 million years.

D. We will continue to study the formation of the first stars and quasars with existing telescopes and, in the future, with the James Webb Space Telescope, to better understand how structure arose in the Universe.

Essential Reading:

Hogan, *The Little Book of the Big Bang: A Cosmic Primer*.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Supplementary Reading:

Dressler, in *The Origin and Evolution of the Universe*.

Hubble Space Telescope, http://hubblesite.org/newscenter/.

Silk, *A Short History of the Universe*.

Wilkinson Microwave Anisotropy Probe, http://map.gsfc.nasa.gov.

Questions to Consider:

1. What if the speed of light were infinite? Would there still be a way for astronomers to look back at galaxies as they appeared long ago?
2. Would you believe the announcement of the discovery of a galaxy at redshift 10,000?

Lecture Twelve

The Accelerating Expansion of the Universe

Scope: In early 1998, two teams announced that observations of Type Ia supernovae provide evidence that the expansion of the Universe is currently speeding up with time, rather than slowing down, as had been expected if attractive gravity were the only relevant force. The supernovae were farther away than is possible unless the expansion is accelerating. The data are now considerably more extensive and reliable, and they still indicate the effects of some kind of cosmic antigravity (now generically called *dark energy*) causing repulsion on large scales in the Universe. Possible ways we might be fooled, such as the presence of intergalactic dust or evolution of Type Ia supernovae over time, have been investigated but do not currently provide reasonable alternatives. Indeed, there is even some evidence for an early epoch of deceleration, when the Universe was young and dense, as expected if the repulsive effect became important only in the last few billion years. Additional measurements are being made to confirm this effect. Unless the weird energy changes character and becomes attractive in the future, the destiny of the Universe is to expand forever at an ever-accelerating rate, rapidly becoming very cold, dilute, and dark.

Outline

I. The Hubble diagram, a plot of galaxy recession speed (usually along the vertical axis) vs. distance (usually along the horizontal axis), demonstrates the expansion of the Universe.

A. Galaxies fall along a straight line, the Hubble law ($v = H_0 d$), whose slope is the current value of the Hubble constant H_0.

B. As mentioned in Lecture Ten, Hubble's law itself does not imply that the speed of a given galaxy increases with time (that is, that the expansion of the Universe is accelerating with time).

1. Instead, Hubble's law implies that at a *given time*, distant galaxies are receding from us faster than nearby galaxies.

2. H_0 is a constant in space, not time. Some astronomers even prefer to call it the *Hubble parameter*.

3. In simple models, throughout the Universe, H_0 decreases with time in proportion to $1/t$. Thus, the speed of a given galaxy at best remains constant with time.

C. In fact, astronomers expected the expansion rate of the Universe to be slowing down (decelerating) with time, because of the presence of galaxies and other gravitating (attractive) matter in the Universe.

1. According to Einstein's general theory of relativity, with normal (attractive) gravity, there are only three possibilities.

2. In each possibility, the expansion decelerates with time, but the ultimate fate of the Universe (that is, whether the expansion ever stops and reverses) depends on the overall *average density*, ρ_{ave}.

D. Let us define *Omega matter* to be $\Omega_M = \rho_{ave}/\rho_{crit}$, where $\rho_{crit} = 3H_0^2/(8\pi G)$ is the *critical density* of the Universe.

1. For $H_0 = 71$ km/s/Mpc, $\rho_{crit} = 9.5 \times 10^{-30}$ g/cm^3.

2. This is the equivalent of only about 6 hydrogen atoms per cubic meter of space.

E. If $\Omega_M > 1$ (i.e., the average density is above the critical density), galaxies separate progressively more slowly with time, but they eventually turn around and approach each other, ending in a hot Big Crunch, also known as a "gnaB giB" (which is Big Bang backwards).

1. In a graph of the distance between two galaxies vs. time, the curve resembles an upside-down "U."

2. A good analogy is an apple thrown up with a speed less than Earth's escape velocity. It starts at zero distance, reaches a maximum value, and eventually falls back down.

3. This is known as a *closed* ("finite") universe, because the two-dimensional analog is the surface of a beach ball.

F. If $\Omega_M = 1$ (i.e., the average density is exactly equal to the critical density), galaxies separate progressively more slowly with time, but as time approaches infinity, the recession velocity approaches zero. Thus, the Universe will expand forever, though just barely.

1. In a graph of the distance between two galaxies vs. time, the curve initially goes up but gradually flattens out, approaching a slope of zero.

2. A good analogy is a ball thrown up with a speed equal to Earth's escape velocity; it continues to recede from Earth ever more slowly, and it stops at t = infinity.

3. This is known as a *flat* or *critical* universe, because according to Einstein's general theory of relativity, light travels along Euclidean straight lines within it.

G. If $\Omega_M < 1$ (i.e., the average density is below the critical density), galaxies separate progressively more slowly with time, but as time approaches infinity, the recession speed (for a given pair of galaxies) approaches a constant, nonzero value. Thus, the Universe will easily expand forever.

1. In a graph of the distance between two galaxies vs. time, the curve keeps going up forever, approaching a constant (but nonzero) slope.

    2. A good analogy is a ball thrown up with a speed greater than Earth's escape velocity; it continues to recede from Earth ever more slowly, but it never stops receding.
    3. This is known as an *open* universe, because in most models, its volume is infinite (as is also the case for the flat universe).

- **H.** An extreme example is an empty universe, with average density 0; $\Omega_M = 0$ and the recession speed (for a given pair of galaxies) is constant throughout time.
    1. In a graph of the distance between two galaxies vs. time, the curve is a straight line of constant slope at all times.
    2. A good analogy is a ball thrown up from the Earth, with the mass of the Earth assumed to be zero; the ball would continue moving with a constant speed forever, neglecting the presence of other masses in the Universe.
    3. In this case, the universe is again *open*, because in most models, its volume is infinite.
- **I.** Throughout the 1990s, many different kinds of measurements of the average density of the Universe suggested that $\Omega_M \approx 0.3$, implying that the Universe should expand forever but gradually slow down.

II. It is possible, however, that a long-range antigravity effect exists, as originally postulated in 1917 by Einstein to explain the apparently static nature of the Universe.

- **A.** The expansion of the Universe had not yet been discovered, and stars didn't seem to be systematically falling toward the Sun; thus, Einstein assumed that the Universe is static.
    1. To counter the attractive force of gravity and prevent collapse, he introduced a mathematical "fudge factor," Λ (the infamous *cosmological constant*), into his equations.
    2. This was not mathematically incorrect, but it was not aesthetically pleasing, and there was no laboratory evidence for repulsive gravity.
- **B.** If a repulsive cosmological constant is present, then another possibility for the Universe is to accelerate with time, after some period of deceleration when the Universe was young and dense.
- **C.** In February 1998, two teams announced the stunning observational conclusion that the expansion of the Universe might indeed be accelerating because of the presence of a cosmological constant.
    1. Thus, we resurrected the idea of a repulsive long-range antigravity effect, but with a slightly larger value than Einstein's original one, leading to net repulsion over large distances (rather than a static universe).
    2. The basic idea is that measurements of distant Type Ia supernovae indicated that they were farther away than they could possibly be in a non-accelerating universe.
    3. Here is an analogy:
        - **a.** If you throw an apple up in the air and measure its distance after 1 second, that distance will be largest if the gravitational force of the Earth is smallest, because the deceleration is then the least.
        - **b.** If there is no gravity, there is no deceleration at all, and the apple doesn't slow down; it reaches the largest possible distance after 1 second.
        - **c.** What we found, effectively, is that the apple is even farther than it could have gotten under the assumption of no gravity.
        - **d.** Thus, it must have accelerated, as though a rocket were attached to it!
    4. But what if the assumed age of the Universe is incorrect?
        - **a.** In the above analogy, what if the apple has been moving for more than 1 second?
        - **b.** It would then reach a larger distance than expected, without any need for acceleration.
    5. It turns out that the detailed argument is *independent* of the assumed age of the Universe.

III. Suppose we allow for the possibility of positive, repulsive Λ.

- **A.** The expansion of the Universe decelerates when the Universe was young, because galaxies were close together and their mutual gravitational attraction was relatively strong.
    1. As the Universe expanded, galaxies receded from each other, and their mutual attraction decreased. The amount of repulsion, on the other hand, increased as space expanded, and eventually, it began to dominate over gravitational attraction.
    2. From this moment onward, the expansion of the Universe accelerated.
    3. In the future, when attractive gravity is minor compared with the repulsive dark energy, the accelerated expansion will approach an exponential; the doubling time for the distance between clusters of galaxies will become a fixed number.
- **B.** At the present time, the Universe expands at some specific rate, independent of the past history or future of the expansion.
    1. Thus, the low-redshift Hubble diagram (recession speed vs. distance, for relatively nearby galaxies) is a straight line, with slope equal to the present-day Hubble constant.
    2. But if we look at a galaxy a few billion light years away, we will be seeing it when the expansion rate was different.

a. The recession speed is simply the slope in the graph of the distance between two galaxies vs. time.

b. The exact value of the slope depends on the density of the universe and on the possible presence of a cosmological constant.

3. This means that curves in the Hubble diagram begin to diverge from the straight line that they all shared at low redshifts (i.e., small distances and small lookback times).

a. The amount and direction of the deviation depend on the values of Ω_M and Λ.

b. For a given distance and for $\Lambda = 0$, the recession speed (i.e., the slope in the graph of the distance between two galaxies vs. time) is largest if $\Omega_M > 1$, smaller if $\Omega_M = 1$, even smaller if $\Omega_M = 0.3$ (the expected value), and smaller still if $\Omega_M = 0$ (an empty universe).

c. Continuing this patter, the recession speed can be even smaller if "$\Omega_M < 0$," but such a value for the matter density of the Universe is unphysical. A better way to write it is $\Lambda > 0$.

4. The way to determine the past history of the expansion of the Universe is to measure the distances of objects at various redshifts and see which of the curves the data match best.

a. Differences in the expansion history are independent of the current value of the Hubble constant.

b. At no point are any assumptions made about the age of the Universe.

IV. The two supernova teams mentioned above (one team led by Brian Schmidt, with Adam Riess doing much of the analysis, and the other team led by Saul Perlmutter) determined the distances and recession speeds (redshifts) of very faint, distant galaxies ($z \approx 0.5$).

A. The distances were measured by finding and observing Type Ia supernovae in these galaxies.

1. If very deep, wide-angle photographs are made of thousands of distant galaxies, the chances of catching a supernova are reasonably good.

2. The same regions of the sky are photographed about a month apart with large telescopes, usually in Chile and Hawaii. Comparison of the photographs with sophisticated computer software reveals the faint supernova candidates.

3. A spectrum of each candidate is obtained, usually with the Keck telescopes in Hawaii. This reveals whether the object is a Type Ia supernova and provides its redshift.

4. Follow-up observations of the Type Ia supernovae provide their light curves.

5. The peak apparent brightness of each supernova, together with the known (appropriately corrected; see Lecture Ten) luminosity of a Type Ia supernova, gives the distance from the inverse-square law.

6. Several dozen supernovae were measured in this manner by early 1998.

B. The results were astonishing: Both teams found that the $\Lambda > 0$ curve best represents our Universe!

1. They concluded, with some hesitancy, that there is a previously unknown component of the Universe with a long-range *repulsive* effect. This is essentially an "antigravity," but only over very large distances.

2. The extra stretching of space makes the supernovae more distant than they would have been had the Universe's expansion decelerated throughout its history.

3. Thus, the expansion of the Universe is now *accelerating* with time rather than decelerating!

C. By the end of 1998, nobody had found an obvious flaw in the data or the interpretation.

1. The editors of *Science* magazine proclaimed this discovery to be the "top breakthrough" in all of science in 1998.

2. On the cover of the 18 December 1998 issue, the caricature of Einstein looks surprised, because we had resurrected the loathsome cosmological constant that he had postulated.

3. Einstein never liked the cosmological constant because of its inelegance, and he renounced it following Hubble's discovery (in 1929) of the expansion of the Universe.

a. After all, no additional forces are needed to keep the Universe expanding if it was born in an expanding state (the Big Bang).

b. According to a book written by George Gamow, Einstein called the cosmological constant the "biggest blunder" of his career—but he does not actually write this in any known publication of his.

c. In retrospect, Einstein's "blunder" was not the cosmological constant idea itself but, rather, in assigning an unlikely value to Λ (i.e., one that leads to a perfectly static universe).

D. Initially, most astronomers and physicists greeted the possible discovery with skepticism. It was such a strange, counterintuitive result, and the data were not yet conclusive.

1. Gradually, however, "Einstein's repulsive idea" caught on, as the evidence became stronger and as alternative explanations were deemed more and more unlikely.

2. For example, what if dust makes the high-redshift Type Ia supernovae dimmer than expected and, hence, at seemingly larger distances?

a. This can be ruled out because normal dust not only dims light, but it also makes an object appear redder—for example, the setting Sun. But the high-redshift Type Ia supernovae have essentially normal colors.

b. Moreover, other kinds of dust were largely ruled out as well.

3. What if the high-redshift supernovae are intrinsically less powerful than the nearby ones, because of evolution of the properties of the stars that produce them? After all, long ago, the white dwarfs had smaller amounts of heavy elements in them, and there may be other effects as well.

a. Then the supernovae would look dimmer than expected, and their distances would be overestimated.

b. This alternative is doubtful because the spectra of the high-redshift Type Ia supernovae closely resemble those of normal, nearby counterparts.

c. However, detailed comparisons have not yet been made, and there might be some differences.

V. Additional evidence was desired.

A. A "smoking gun" would be to see that Type Ia supernovae at even higher redshifts appear brighter than expected in the dust or evolution hypotheses.

1. If dust or evolution cause the redshift 0.5 supernovae to look dimmer than expected, then supernovae at even higher redshifts should look even dimmer (beyond what is explained from just their extra distance), because of the presence of even more dust or evolution as one probes to greater lookback times.

2. On the other hand, if Λ is causing the redshift 0.5 supernovae to look dimmer than expected, then at redshift 1 and beyond, supernovae should begin to look somewhat brighter than expected in an empty (constant expansion) universe.

a. The reason is that beyond redshift 1, we are looking back to a time when the Universe was decelerating rather than accelerating.

b. Galaxies were sufficiently close together that gravitational attraction dominated over cosmic repulsion.

c. Thus, distances grew more slowly with time than in an empty universe.

3. SN 1997ff, a probable Type Ia supernova at redshift 1.7 (i.e., with a lookback time of about 10 billion years), was fortuitously observed with the Hubble Space Telescope.

a. Analysis of the data, led by Adam Riess, showed that the object was significantly brighter than expected if dust or evolution were the culprits.

b. The data, though uncertain, were most consistent with a previously decelerating (and currently accelerating) Universe!

4. Additional data from the past few years also tend to support this conclusion, although more work is still needed to be certain.

B. The latest results, based on an analysis of more than 200 Type Ia supernovae, confirm that the cosmological constant appears to be nonzero.

1. Combining the supernova data with other relevant results, we find that $\Omega_\Lambda \approx 0.72$ and $\Omega_M \approx 0.28$, where Ω_Λ is simply Λ expressed in the same units as Ω_M—specifically, $\Omega_\Lambda = \Lambda c^2/(3H_0^2)$.

2. This is essentially identical to results announced in February 2003 from the WMAP satellite: $\Omega_\Lambda \approx 0.73$ and $\Omega_M \approx 0.27$, using independent techniques.

3. The fact that two different methods yield such good agreement gives us considerable confidence in the conclusion.

C. What is the weird repulsive "stuff"? It goes by various names, such as *vacuum energy* and *funny energy*, but now the generally accepted term is *dark energy*.

1. This should *not* be confused with *dark matter*, which is gravitationally attractive (as is luminous matter).

2. It also cannot be antimatter, which is gravitationally attractive.

3. In Lecture Fourteen, we will discuss its possible nature in greater detail.

D. Unless the repulsive stuff changes in the future, the Universe will expand forever, even if it is closed (finite in volume).

1. Because distant galaxies are receding from each other faster and faster, eventually, they will fade away: They will become so distant that their light cannot reach us.

2. Thus, the Universe will become cold, dark, and essentially devoid of matter even faster than it would have with a low matter density ($\Omega_M \approx 0.3$) but zero cosmological constant.

3. Instead of ending in a hot, fiery Big Crunch ($\Omega_M > 1$), the Universe will end as if "in ice"—reminiscent of Robert Frost's famous poem "Fire and Ice."

Essential Reading:

Kirshner, *The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos*.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Supplementary Reading:

Goldsmith, *The Runaway Universe.*

Livio, *The Accelerating Universe: Infinite Expansion, the Cosmological Constant, and the Beauty of the Cosmos.*

Questions to Consider:

1. Discuss why Ω_M, the ratio of the average matter density to the critical density of the Universe, is such an important parameter.
2. Besides cosmic evolution of Type Ia supernovae and the possible presence of obscuring dust, can you think of any other astrophysical reason (not having to do with accelerated expansion) why high-redshift Type Ia supernovae might appear fainter than expected?

Lecture Thirteen

The Stuff of the Cosmos

Scope: Besides observations of Type Ia supernovae, there are now several other types of data that confirm the presence of dark energy and allow us to quantify it. Specifically, detailed measurements of the cosmic microwave background radiation, most recently those obtained with the WMAP satellite, show that the Universe is geometrically flat on large scales, and this requires that the total energy density of the Universe be 1.0 in certain units. But the energy density of luminous and dark *matter* amounts to only 0.27 (i.e., 27%) in the same units. The remainder, 0.73 (73%), cannot be uniformly distributed gravitating matter, because it would have adversely affected the growth of large-scale structure, such as clusters of galaxies, from the initial variations in the density of the Universe. It is more likely to be the repulsive dark energy previously suggested by the supernova observations. We live in a bizarre Universe where the visible matter constitutes less than 1% of all that exists. Hot gas adds roughly another 4%. An unknown form of dark matter, probably consisting of exotic subatomic particles left over from the Big Bang, contributes 22% to the total mass/energy content of the Universe. But the dark energy dominates at 73%, and its nature is a mystery that is more fully discussed in the next lecture.

Outline

I. Although the existence of repulsive dark energy was first convincingly suggested by the observations of distant Type Ia supernovae, additional compelling evidence now comes from the cosmic microwave background radiation (CMBR), whose origin we discussed in Lecture Eleven.

   A. Although the CMBR is very uniform throughout the sky (after taking into account the Earth's motion relative to it), there are tiny fluctuations (variations) of about 1 part in 100,000 in its temperature.

   B. These fluctuations of about 30-millionths of a degree (compared with the roughly 3 K temperature of the CMBR) correspond to slight inhomogeneities ("clumps" and "holes") in the density of matter at the time of recombination, 380,000 years after the Big Bang.

      1. Photons escaping from these clumps and holes would have a slightly different redshift than those coming from regions of average density.

      2. There are several relevant processes, but perhaps the easiest to understand is that photons lose more energy when they escape from stronger gravitational fields (as in the clumps), and they lose less energy when they escape from weaker gravitational fields (as in the holes).

    - **3.** The different redshifts would translate into slight fluctuations in the associated temperature of the radiation.
  - **C.** The slightly overdense and underdense regions are the “seeds” from which large-scale structure (clusters of galaxies, superclusters, and voids) grew in the Universe.
    - **1.** They are the imprints of minuscule ripples in the distribution of matter established shortly after the Big Bang.
    - **2.** The ripples were probably a consequence of quantum fluctuations in the matter density.
  - **D.** In 1992, the Cosmic Background Explorer (COBE) satellite found the first evidence for the fluctuations, on angular scales of about 10 degrees. Subsequently, other studies found similar fluctuations on smaller angular scales, less than 1 degree.

- **II.** It is these subsequent studies that provided the crucial evidence for dark energy.
  - **A.** Among the most well known CMBR measurements in the past few years was that of BOOMERANG, which consisted of a microwave telescope in a gondola, lifted high into the Earth’s atmosphere by a balloon launched from the Antarctic.
    - **1.** It is necessary to go above much of the Earth’s atmosphere in order to make accurate measurements of the microwaves.
    - **2.** The cold temperatures of Antarctica freeze out water vapor, making the atmosphere very dry—another big bonus for the measurements.
    - **3.** The prevailing atmospheric wind currents made the balloon drift almost in a circle, and it landed near the place of launch after about 10 days.
    - **4.** Other, similar experiments were conducted by other groups of researchers.
  - **B.** The results of these observations were spectacular maps of the tiny fluctuations in the CMBR temperature across the sky.
    - **1.** They revealed that the angular diameter of a typical fluctuation is about 1 degree, about twice that of the full moon.
    - **2.** It turns out that certain “preferred” physical sizes are expected theoretically, because early in the Universe, the matter and photons vibrated like sound (acoustic) waves in a wind instrument, which also has a set of “preferred” wavelengths.
      - **a.** The details are complicated, but the basic picture can be glimpsed by noting that clumps of matter tended to contract because of the pull of gravity, but radiation (photons) exerted an outward pressure, causing the clumps to expand. This caused the formation of sound waves.

      - **b.** Some wavelengths grew, and others were suppressed, as the Universe expanded.
  - **C.** But the mathematical relationship between the *physical* and *angular* sizes of an object depends on the overall geometry of space.
    - **1.** With flat, Euclidean geometry, light travels along familiar straight lines, and the angular size of an object of a given physical size is inversely proportional to its distance.
    - **2.** With spherical (i.e., positively curved) geometry, light travels along paths that are curved in such a way that an object of given physical size and distance looks *larger* than in flat (Euclidean) space.
    - **3.** With hyperbolic (i.e., negatively curved) geometry, light travels along paths that are curved in such a way that an object of given physical size and distance looks *smaller* than in flat (Euclidean) space.
  - **D.** The observed angular diameter of the typical variations, when combined with the expected physical diameter, corresponds to what is expected in flat space. Thus, the CMBR maps tell us that the Universe is Euclidean (spatially flat) over very large distances!
  - **E.** Now let’s bring in the general theory of relativity. Overall flatness of the Universe means that the average total density (of matter, normal energy, and other energy) is equal to the critical density, $\rho(\text{crit}) = 3H_0^2/(8\pi G)$.
    - **1.** In other words, the ratio of the average density to the critical density, $\Omega(\text{total})$, is 1.0 in a flat universe.
    - **2.** However, many existing measurements had strongly suggested that the *matter* density of the Universe, Ω_M, is only about 0.3.
    - **3.** If the total mass/energy of the Universe $\Omega(\text{total}) = 1.0$ and $\Omega_M = 0.3$, then the difference is 0.7 ($\Omega_x = 0.7$, where x is used to denote the mysterious new “stuff”).
      - **a.** This remaining component, $\Omega_x = 0.7$, could not be associated with clusters of galaxies, because a complete census had already been made of the masses of clusters—indeed, that is one of the ways in which we find that $\Omega_M = 0.3$.
      - **b.** Further, most of it could not be uniformly distributed but gravitating “hot dark matter” consisting of very rapidly moving particles (i.e., relativistic, close to the speed of light), such as neutrinos, because it would not have allowed the formation of galaxies and clusters of galaxies.
      - **c.** The last alternative is some sort of energy that is uniformly distributed throughout the Universe but does not impede the formation of large-scale structure, such as filaments of galaxies, superclusters, and voids.

- **4.** The repulsive dark energy suggested by the observations of distant Type Ia supernovae is consistent with this last alternative.
  - **a.** Agreement of the predictions of computer simulations of cluster formation with the observations is achieved with a combination of clumped dark matter and uniform dark energy.
  - **b.** Moreover, the observed distribution of clusters could have come from the initial fluctuations measured by the CMBR only if the dark energy is repulsive and started dominating the energy density of the Universe relatively recently (in the past few billion years) rather than at early times.

III. A NASA spacecraft currently aloft, WMAP, is mapping the sky at 30 times the resolution of COBE and has provided even more evidence for dark energy.

- **A.** The probe is named after David Wilkinson, an important member of the COBE and WMAP teams and a member of the original Princeton team that was among the first to understand the CMBR.
- **B.** The results of WMAP's first year of data were released in February 2003.
  - **1.** The spectacularly detailed map of the entire sky shows temperature variations measured in millionths of a degree.
  - **2.** The results for a variety of cosmological parameters, derived by studying various aspects of the inhomogeneities, are so precise that they have greatly helped transform cosmology into a precision science.
- **C.** The data, when linked with other observations, show conclusively that the Universe is flat or nearly flat.
  - **1.** $\Omega(\text{total}) = 1.0$, with an uncertainty of only 2%.
  - **2.** This does not necessarily imply that the Universe is infinite. If $\Omega(\text{total}) = 1.01$, for example, the Universe has positive curvature and is shaped like a three-dimensional version of the spherical balloon.
    - **a.** If so, the radius of curvature is much larger than the distance to which we can see.
    - **b.** This is like standing on the Great Plains and trying to see the Earth's curvature.
    - **c.** Certain "inflationary" theories of the early Universe, in fact, suggest that the Universe is immensely larger than the distance to which we can see; thus, finding a flat, or nearly flat, geometry is to be expected.
- **D.** The WMAP results completely confirm those obtained from the Type Ia supernovae.

  - **1.** Despite widespread (and justified) initial skepticism among other astronomers, both of the high-redshift supernova teams were correct in their conclusions.
  - **2.** Type Ia supernovae, in conjunction with other constraints, yield $\Omega_M = 0.28$ and $\Omega_\Lambda = 0.72$; for comparison, the WMAP measurements, in conjunction with the same constraints, give $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$.
  - **3.** This agreement is immensely satisfying to the supernova researchers, as well as to the WMAP team.

IV. The composition of the Universe, according to WMAP, is 27% matter and 73% dark energy, with $\Omega(\text{total}) = 1$.

- **A.** However, we have long known that most of the matter is "dark"—it doesn't glow at optical or other easily measurable wavelengths.
  - **1.** Several decades ago, Vera Rubin found that the speed of rotation of spiral galaxies is about the same far from the center as it is closer in.
  - **2.** This was inconsistent with the observed distribution of visible stars in these galaxies: They thinned out too quickly at large distance and could not provide enough gravitational pull to account for the observed rotation speeds.
  - **3.** Thus, Rubin concluded that there must be large quantities of dark matter in galaxies.
  - **4.** Observations are most consistent with theory if most of the dark matter is distributed in a halo, rather than in the flat disk.
- **B.** As far back as 1933, in fact, Fritz Zwicky of Caltech concluded that dark matter dominates large clusters of galaxies.
  - **1.** The individual galaxies within a cluster move so rapidly that they would quickly escape from the cluster unless there was dark matter exerting an additional gravitational pull on them.
  - **2.** Zwicky's brilliant conclusion was so far ahead of its time that he was largely ignored.
  - **3.** It didn't help that he was quite an arrogant and abrasive fellow; colleagues didn't like to interact with him.
- **C.** We now know that stars and visible gas are only 0.5% to 1% of the total mass/energy content of the Universe, $\Omega(\text{total}) = 1$. Of what does the remaining matter contribution (about 26%) consist?
  - **1.** In *Understanding the Universe*, 1998, I mentioned that one class of dark matter candidates is known as MACHOs (*massive compact halo objects*).
    - **a.** These include black holes, neutron stars, white dwarfs, brown dwarfs, and free-floating massive planets ("Jupiters").

        - **b.** Such objects can, in principle, gravitationally lens background stars, such as those in the Large and Small Magellanic Clouds, satellites of the Milky Way galaxy.
        - **c.** The brightening of the background star is the same regardless of wavelength, because it is caused by the bending effect of space-time.
    - **2.** Initial results suggested that much of the halo might consist of MACHOs: Quite a few lensing events had been detected.
        - **a.** However, further study has shown that the few lenses with known distances were stars in the Magellanic Clouds themselves, not halo objects.
        - **b.** It is now thought that < 20% of the mass of the halo consists of MACHOs.

D. What candidates are left for the dark matter?
- **1.** Neutrinos probably contribute at most 0.3% of the total mass/energy of the Universe.
- **2.** "Golf balls"—by which we mean small, solid objects that would be very difficult to detect—remain candidates, but we know of few, if any, ways in which they are formed.
- **3.** Gas having a temperature of about 1 million degrees is a strong candidate; until recently, we did not have sufficiently sensitive instruments to detect it.
    - **a.** Indeed, new measurements (announced in 2003) with the Chandra X-ray Observatory and other telescopes have detected X-rays from tenuous hot gas in the halos of galaxies and in loose groups of galaxies, analogous to the much hotter gas that has long been known in massive clusters of galaxies.
    - **b.** These very important studies suggest that 3% to 4% of the total mass/energy of the Universe is in the form of hot gas.
- **4.** Exotic subatomic particles remain a possibility, as well; see below.

E. The hot gas, together with stars and optically visible gas, account for 3.5% to 5% of the total mass/energy density of the Universe.
- **1.** In fact, we now know this total quite accurately: 4.4% of the total mass/energy of the Universe consists of normal neutrons and protons (collectively called *baryons*).
    - **a.** This value is obtained from WMAP.
    - **b.** Quite independently, studies of the amount of primordial deuterium (formed during the first few minutes after the Big Bang) yield the same number.
- **2.** Including neutrinos (0.3% of the total mass/energy), only about 5% of the Universe (i.e., $\Omega = 0.05$) consists of matter to which we can relate, and only about 0.5% to 1% of the Universe consists of matter we can optically see.

F. Exotic subatomic particles, probably left over from the Big Bang, are the leading candidate for the rest of the matter content of the Universe (about 22% of the total mass/energy).
- **1.** One possibility is WIMPs (*weakly interacting massive particles*).
- **2.** However, we do not really know what this dark matter component will turn out to be.

G. As discussed extensively above, the remaining 73% of the total mass/energy is dark energy—and we *truly* don't know what it is.

H. It is rather disconcerting that, at the present time, we have no direct knowledge of the contents of 95% of the Universe!
- **1.** Twenty-two percent is dark matter that does not consist of normal matter, but we know little else.
- **2.** Seventy-three percent is dark energy, whose nature is even more of a mystery.

Essential Reading:

Lemonick, *Echo of the Big Bang*.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Supplementary Reading:

Rubin, *Bright Galaxies, Dark Matter*.

Smoot and Davidson, *Wrinkles in Time*.

Wilkinson Microwave Anisotropy Probe, http://map.gsfc.nasa.gov.

Questions to Consider:

1. Discuss the significance of tiny inhomogeneities, variations or "ripples," in the cosmic microwave background radiation. What is their origin, what did they later become, and how do they help us decipher the overall geometry of the Universe?
2. Think of possible candidates for dark matter that consists of normal neutrons and protons but would be hard to detect observationally. How could you confirm them or rule out their existence?

Lecture Fourteen

Dark Energy—May the Force Be with You

Scope: The presence of dark energy having strange properties is now rather compelling, and it is shaking the foundations of theoretical physics. Though its energy density is positive, its pressure is negative, which leads to repulsion and an exponential expansion of space—an effect reminiscent of the very early Universe, when we think it went through a stage of inflationary expansion. This lecture explores, in more detail, the possible origin of dark energy. Specifically, it might be the result of a non-perfect cancellation of *quantum fluctuations*—virtual particles created literally out of nothing, as a consequence of quantum physics. There is strong experimental evidence for the existence of virtual particles, such as the Casimir effect; to gain some understanding of this evidence, the lecture describes different types of infinity. On the other hand, there are several problems with quantum fluctuations as an explanation for the dark energy: Why is the effect so small, and why is it roughly comparable to the gravitational attraction of dark matter at the present time? Thus, physicists have sought other possible origins for dark energy. The most extensively investigated idea is *quintessence*—an energy field that is repulsive and, in a sense, can be thought of as the latent heat of space associated with an unbroken (or recently broken) symmetry.

Outline

I. The last two lectures described the now rather compelling evidence that the Universe's energy density is dominated by dark energy of a repulsive nature: It is making space itself expand at a progressively faster rate.

- **A.** This discovery is shaking the foundations of theoretical physics.
  - **1.** Researchers throughout the world are trying to understand it, and it is a hot topic at physics and astronomy conferences.
  - **2.** Let me try to explain the meaning and possible origin of the dark energy.
- **B.** In Isaac Newton's theory of gravity, its effect is always attractive.
  - **1.** Apples fall from trees to the ground, for example.
  - **2.** The only relevant factors are the masses of the two objects (m_1 and m_2) and the distance (d) between them: $F = Gm_1m_2/d^2$, where G is the constant of universal gravitation.
- **C.** However, in Einstein's general theory of relativity, gravity can sometimes exert repulsion!
  - **1.** There are actually *two* sources of gravity: the mass of an object (actually, its matter density ρ) and its pressure (P).
  - **2.** Although this is counterintuitive, *outward* (i.e., positive) pressure, such as the pressure of the Earth exerted on your feet, has an *attractive* gravitational effect.
    - **a.** This means that you weigh a bit more on Earth, because of its pressure, than you would if the mass of the Earth were all that mattered.
    - **b.** The Earth's pressure is so small that this effect is negligible.
    - **c.** On the surface of a neutron star, however, the effect is substantial, because of the neutron star's large pressure.
    - **d.** This effect actually helps limit the mass of the most massive stars: They become unstable and gravitationally collapse at a smaller mass than would have been expected from Newton's formulation of gravity.
- **D.** Applying the general theory of relativity to the entire Universe, one finds that the rate of change of the expansion rate produced by a substance is proportional to $-(\rho c^2 + 3P)$, the negative of its density (times the speed of light squared) plus three times its pressure.
  - **1.** For all *normal* types of matter and energy, both the density and pressure are positive, so the rate of change of the expansion is negative—in other words, the expansion of the Universe slows down (decelerates) with time.
  - **2.** However, *suppose* you have a substance whose pressure is *negative*—in fact, more negative than $-(1/3)\rho c^2$.
  - **3.** Then $3P$ is a negative number of larger absolute value than ρ, and the sum $(\rho c^2 + 3P)$ is negative. The rate of change of the expansion is, therefore, positive, and the expansion *accelerates* with time!
  - **4.** We think that the dark energy is a substance of this kind, with $P < -(1/3)\rho c^2$.
- **E.** Accelerated expansion of space reminds us of the theory of inflation of the early Universe that was discussed in the 1998 course on astronomy and will be summarized in Lecture Sixteen.
  - **1.** Indeed, we appear to be entering a new inflationary epoch of the Universe!
  - **2.** Unless the repulsive force changes sign in the future, the cosmos will expand eternally, growing ever colder and darker at an inflationary rate.

II. We don't know what the dark energy is; hundreds of ideas are currently being considered.

- **A.** One possibility, however, is a vacuum energy produced by *quantum fluctuations*.
  - **1.** According to the Heisenberg Uncertainty Principle of quantum physics, we cannot know the exact energy of each point of space.

The energy at each point must, therefore, be randomly fluctuating; otherwise, we would know that its value is zero.

2. *Virtual* particles of energy, ΔE, spontaneously form and live for a time, Δt. The product $\Delta E \Delta t$ is not larger than about $h/2\pi$, where h is Planck's constant, a very small number.
3. These quantum fluctuations represent a temporary, fleeting quantum violation of the *classical* law of the conservation of energy.
4. We know that virtual pairs of particles (e.g., electrons and positrons) do actually form and subsequently disappear in the Universe.
    - **a.** If this were *not* the case, then the predicted energy levels of the hydrogen atom (and other atoms) would disagree with the experimentally measured levels, yet the agreement is exact.
    - **b.** There is a difference, known as the *Lamb shift*, between the energy levels predicted when this effect is and is not taken into account.
5. Studies of the interactions between real particles (e.g., protons and electrons) exchanging virtual particles (e.g., virtual photons) is a well-developed branch of physics known as *quantum electrodynamics*; it was developed by several people, including the late Richard Feynman, who won the Nobel Prize for this work.

B. It had always been assumed that there are just as many negative energy fluctuations as there are positive energy fluctuations (the positive fluctuations essentially "borrow" energy from negative fluctuations), so that the net effect on the energy density of space is exactly zero.

1. However, if there were a net *positive energy* associated with the quantum fluctuations (resulting from an incomplete cancellation), then it would have a *negative pressure* with $P = -\rho c^2$, and space would expand at an accelerating rate wherever this vacuum energy dominates over other, more normal, forms of energy.
2. This could be the cause of the observed accelerating expansion of the Universe!

C. The possibility that a vacuum can have different values for the pressure, depending on circumstances, is well illustrated with the Casimir effect, which has been demonstrated in laboratories.

1. Set up two thin, essentially massless (so gravity can be ignored), conducting metal plates that are very close to each other (spacing L), with their faces parallel. The plates are grounded; they have no free charges.
2. It is observed that the plates move closer to each other (i.e., L decreases), as if by magic!
3. What is actually happening is that vacuum quantum fluctuations occur both outside the plates and between the plates.

4. Outside the plates, the virtual photons (or the waves associated with the virtual particles) can have *any* wavelength, with no restrictions.
5. Between the plates, however, the wavelengths are restricted, much like the standing waves in a wind instrument having two closed ends.
    - **a.** There must be a node (no oscillation of the electric or magnetic fields) at each plate, because currents are set up in the plates that cancel the fields if they are nonzero.
    - **b.** This is analogous to the nodes at the ends of a wind instrument, where the molecules can't vibrate back and forth.
    - **c.** The longest wave has a wavelength $\lambda = 2L$, the next one has $\lambda = (2/2)L = L$, the next has $\lambda = (2/3)L$, followed by $\lambda = (2/4)L = L/2$, and $(2/5)L$, and so on. In general, then, the allowed wavelengths are given by $\lambda = (2/n)L$, where $n = 1, 2, 3, 4, \ldots$.
6. The number of possible waves between the plates is infinite, but it is a *smaller infinity* than the one outside the plates, where all possible wavelengths are allowed.
    - **a.** The concept of infinity is weird, as we already encountered in Lecture Ten.
    - **b.** Infinities can, in some cases, have different sizes.
    - **c.** For example, the irrational numbers, such as π, e, π^e, and so on, which cannot be expressed as nonrepeating rational fractions, constitute an *uncountable infinity* that is fundamentally larger than the counting numbers and the rational numbers (known as *countable infinities*).
7. Thus, the pressure outside the plates is larger than between the plates, so the plates get pushed together!

III. The vacuum fluctuations discussed above give rise to a *cosmological constant*, Λ, like that envisioned by Einstein.

A. They are a property of empty space, and as the amount of space grows, the cumulative effect increases, since the energy density (i.e., the energy per unit volume) remains constant.

1. It sounds like one is getting energy from nothing as the volume of space grows, but actually the positive energy of the vacuum fluctuations is exactly cancelled by the negative gravitational potential energy.
    - **a.** Both energies are growing in absolute value, but the gravitational energy of the vacuum is always exactly the *negative* of the vacuum energy itself.
    - **b.** That gravity is associated with negative energy is easily seen: When one drops an apple, it gains energy of motion (kinetic energy) as it falls, but this is exactly balanced by a larger negative gravitational energy, so the sum remains constant.

2. Such growth is exponential: In a given time interval, all lengths double, and in subsequent time intervals, all lengths double again and again.
   a. The exponential growth occurs only when other forms of energy are completely negligible compared with the vacuum energy.
   b. This is not the case at present in the Universe: $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$, so Ω_M is not negligible. The current expansion of the Universe is accelerating, but it is not yet exponential.
3. There are at least two major problems, however, with vacuum fluctuations being the dark energy and the reason for the acceleration of the Universe.

B. The first problem is that when theoretical physicists calculate the expected value of Ω_Λ using reasonable assumptions and approximations, they get a value of order 10^{120}, a far cry from the measured value of only 0.73!

1. Even when certain other assumptions are made, they can bring the expected value of Ω_Λ down to about 10^{50} but not much lower.
2. Either way, this is the biggest error ever in theoretical physics!
3. This error was recognized even before the Type Ia supernova measurements: If Ω_Λ were as large as the above estimates, we would definitely not exist, because the Universe would have expanded far too quickly to allow galaxies and stars to form.
4. Theorists assumed, then, that there is some yet-unknown principle in the correct theory of elementary particles (supersymmetry, strings, and so on, to be briefly discussed in Lecture Fifteen) that makes the positive and negative vacuum fluctuations *exactly cancel* each other, yielding $\Omega_\Lambda = 0.000$.
5. These physicists were incredibly surprised when we announced the results of the Type Ia supernova observations: Ω_Λ is small (about 0.7) but not exactly zero.
6. It is extremely difficult to find a compelling, self-consistent theory that produces a nearly exact, but not *perfectly exact*, cancellation between positive and negative fluctuations.
7. Indeed, the problem seemed so intractable that in 1998, at a conference of scientists, a very famous theoretical physicist commented that we observational astronomers *must* be incorrect; the Universe *can't possibly* have such a bizarre near-cancellation!
8. My opinion was that this is an observational problem: Either Ω_Λ is 0 or it isn't, regardless of whether theorists have figured it out yet.

C. The second major problem is that it seems strange that the normal matter density (including dark matter), Ω_M, is nearly equal to the dark energy density, Ω_Λ.

1. Of all the possible ratios they could have (10^9, or 10^{-6}, or whatever), why is the ratio nearly 1 (i.e., $\Omega_\Lambda/\Omega_M = 0.73/0.27 \approx 3 \approx 1$)?
2. In fact, Ω_M used to be much larger, but is decreasing with time as the Universe expands and matter gets progressively more rarefied.
3. Conversely, Ω_Λ used to be much smaller, but is increasing with time as the Universe expands and the total amount of space (and, hence, vacuum energy) increases.
4. In other words, the ratio Ω_Λ/Ω_M used to be very small, and in the future, it will be very large. Why is it nearly unity right now, while we are around to see it this way? Over most of the history and future of the Universe, the ratio will be very different from unity.

IV. Largely because of this "fine tuning" that seems to be associated with the cosmological constant, theoretical physicists have been trying to find other possible origins for the dark energy.

A. Generically, these alternatives are called *quintessence*—similar to Aristotle's celestial "fifth essence." (Aristotle's four essences were earth, air, fire, and water.)

1. Fundamentally, quintessence refers to possible new forces or fields that might be causing the expansion of the Universe to accelerate and whose energy density is $\Omega_x = 0.73$ (i.e., $1.0 - \Omega_M$).
2. The motivation is to find a solution that is more "natural"—one that easily produces the observed value of Ω_x and does not put us in a special time.

B. For example, the dark energy might be associated with a state of unbroken symmetry, such as two unified forces that should have broken apart (but didn't break apart) in the past, when the temperature of the Universe fell below some critical value.

C. Let me show you the example of a supercooled sodium acetate solution, as can be found in "heat packs" sold by camping stores.

1. Its lowest energy state at room temperature is to be a solid, but if you heat it in a pot of boiling water, then let it cool to room temperature, it will remain a liquid.
2. This supercooled liquid has more energy (latent heat) than normal at room temperature; in fact, that's what keeps it in the liquid state.
3. The extra energy corresponds to dark energy, but here the analogy fails: The liquid does *not* exponentially inflate in size.
4. However, if the liquid is perturbed enough by bending a metal disk inside, the phase transition to a liquid *crystalline* form begins, and the latent heat escapes.
5. The liquid crystal solidifies as the heat is dissipated into the room, eventually becoming rock solid.

D. By drawing a graph of what has just been described, we can plot a curve of the energy of a system vs. its symmetry parameter, often denoted by φ (Greek lower-case *phi*), for a variety of temperatures. A ball on the curve represents the actual state of the system.

1. Above a certain critical temperature, the lowest energy state is one of unbroken symmetry (φ = 0)—in our case, the liquid. The ball simply rolls down to the bottom of the curve.
2. Below the critical temperature, the curve's character changes: The lowest energy state is one of *broken* symmetry (in our case, a rock-solid crystal).
3. However, the system can remain in a state of unbroken symmetry (in our case, liquid) if the curve has the right shape—for example, a dimple at φ = 0 in which the ball can sit. The latent heat is the "extra" energy that it now contains.
4. If the system is perturbed, the ball can pop out of the dimple and start rolling down the curve, thereby breaking symmetry and releasing its latent heat. In our case, the liquid starts to crystallize.
5. Different substances are characterized by curves that differ from those drawn here.
6. For example, there might not be a dimple or, because the curve can be quite flat, the breaking of symmetry occurs slowly.

E. In the case of the Universe, the latent heat is the dark energy that drives the accelerated expansion. As long as that energy is nonzero, accelerated expansion can occur.

F. Literally hundreds of other models have been proposed, many of which are variations on the above theme.

1. The shapes of the curves vary widely, and the underlying physical principles can differ.
2. In essence, these are among the different forms of quintessence.

G. We don't really know which of these ideas, if any, apply to the real Universe.

1. One way to help find out is to measure the history of the expansion rate in greater detail to see how it has changed with time.
2. We are now in the process of doing this with hundreds of distant supernovae.
3. Maybe by the time of the next update to these lectures, we will be able to say with greater confidence whether vacuum fluctuations or some other hypothesis is most likely to be the correct explanation for the current epoch of acceleration.

Essential Reading:

Guth, *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*.

Krauss, *Quintessence*.

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Supplementary Reading:

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Livio, *The Accelerating Universe: Infinite Expansion, the Cosmological Constant, and the Beauty of the Cosmos*.

Questions to Consider:

1. Given that $E = mc^2$ (an equation many of us learned on our mother's knee), stating the equivalence of mass (matter) and energy, can we conclude that dark matter is the same as dark energy?
2. Can you think of some kind of analogy that might make the concept of *negative pressure* more intuitive and understandable?

Lecture Fifteen

Theories of Everything and Hidden Dimensions

Scope: The possible explanations of dark energy in the previous lecture are rather abstract and difficult to comprehend, and they are still incomplete. Our understanding is so limited that we don't even know whether the repulsive effect will last forever or eventually reverse sign and cause the Universe, ultimately, to collapse. However, the dark energy provides us with a chance to test candidate *theories of everything*, which attempt to unify the known forces of nature. Unification is necessary because the two major pillars of modern physics, general relativity (a quantitative description of gravity) and quantum mechanics (which governs the behavior of particles on very small scales), are mutually inconsistent. The Big Bang, the singularity in a black hole, and even the structure of empty space cannot be understood without a quantum theory of gravity. The most extensive work in this area has been done on *string theories*, which postulate that every elementary particle is a different mode of vibration of a tiny energy packet known as a *string*. One consequence of such theories is the existence of multiple unseen dimensions, in most cases, extremely tiny but perhaps a few very large ones, as well. Gravity might be a strong force that resides primarily in another dimension, distinct from our known three spatial dimensions. Tests for the presence of hidden dimensions are now being conducted.

Outline

I. We continue our discussion of dark energy and the accelerating Universe, or "RdarkG and the XLR8N Universe." What's in store for the future? Will space continue to expand forever?

- **A.** As long as the dark energy is repulsive, the expansion of the Universe will continue to accelerate, and we will see a progressively smaller fraction of the entire Universe.
  - **1.** Other clusters of galaxies will be whisked away from us, eventually becoming so distant that any new light they emit will never reach us.
  - **2.** Galaxies in the Local Group will merge into a single enormous galaxy.
  - **3.** Stars in our galaxy will eventually burn out.
  - **4.** Because the proton is thought to be unstable over long time intervals, the corpses of dead stars (white dwarfs, neutron stars) will subsequently disintegrate.

  - **5.** There will be nothing but low-energy photons, neutrinos, and a few other elementary particles in the very cold, dark, dilute Universe.
- **B.** However, it is possible that the Universe won't expand forever.
  - **1.** If the dark energy eventually "decays" to form normal matter (either dark or luminous) with attractive gravity and if Ω(total) is actually a tiny bit greater than 1.0, the Universe will ultimately collapse.
  - **2.** Also, given that we don't know the nature of the dark energy, its sign could conceivably change in the future, becoming attractive, rather than repulsive.
  - **3.** For example, Andrei Linde finds that "N=8 supergravity theories" have the generic property that the dark energy eventually becomes attractive—suggesting that the hot Big Crunch ("gnaB giB") might someday occur, after all.

II. Dark energy provides us with an opportunity to test modern *theories of everything* that attempt to unify the forces of nature into a single comprehensive framework.

- **A.** Such theories should make predictions about the energy content of the Universe and the characteristics of the energy.
- **B.** To gain some insight into this, let's consider the four known "fundamental" forces in nature.
  - **1.** *Gravity* is extremely weak, but it acts over large distances, and all types of matter (and energy) are affected in the same way, regardless of charge or other properties.
  - **2.** *Electromagnetism* is about 10^{39} times stronger than gravity, and it acts over large distances, but only charged or magnetized objects are affected.
  - **3.** The *strong nuclear force* is even stronger than electromagnetism, but it operates only over a very short range.
    - **a.** The protons and neutrons in an atomic nucleus are held together by the strong force.
    - **b.** We now know that the strong force is actually just the residue of a more fundamental (and even stronger) *color force* that binds quarks together. However, for historical purposes, we will still refer to it as the strong force.
  - **4.** The *weak nuclear force* operates only over a very short range. It governs certain types of radioactive decay, such as the neutron becoming a proton, an electron, and an antineutrino.
- **C.** It has been shown that the electromagnetic and weak forces are different *manifestations* of a single more fundamental force called *electroweak*.

1. The two forces are different at low energies, but when protons collide with energies corresponding to 100–1000 proton masses, they behave in a similar manner.
2. We say that the "symmetry is broken" at low energies. In high-energy interactions, the two forces cannot be distinguished and, hence, appear *symmetric* (unified).
    - **a.** A useful analogy is a coin flicked along the surface of a table.
    - **b.** When it is spinning rapidly at high energies, it appears symmetric, but we see either heads or tails when it comes to rest.
3. Symmetry plays an important role in theories of particles and forces. In the popular *supersymmetry* theories, each known particle has a supersymmetric partner.
    - **a.** Among these are the *selectron*, the *sneutrino*, the *photino*, and others.
    - **b.** Unfortunately, none of the partner particles has ever been detected!

D. *Grand unified theories* (GUTs) attempt to unify the electroweak and strong nuclear forces.

E. *Theories of everything* (TOEs) attempt to unify the GUT force and gravity in a single *superunified* force.

1. This is a difficult task. Gravity presents a real enigma: Why is it so weak?
    - **a.** A small magnet can lift a paper clip, for example, despite the entire gravitational field of the Earth pulling down on that paper clip.
    - **b.** For the electric and gravitational forces in a hydrogen atom to be equal, electrons and protons would need masses of 10^{19} times the mass of a proton.
    - **c.** This is known as the *Planck mass*.
2. Another problem is that the two great pillars of modern physics, general relativity (GR) and quantum mechanics (QM), are mutually inconsistent and incompatible.
    - **a.** QM is incredibly successful on small scales, that is, with atoms, molecules, subatomic particles, and so on. It deals with small masses in small volumes.
    - **b.** GR is incredibly successful with large (or small) masses over large volumes, that is, galaxies, stars, planets, and so on.
    - **c.** But there is no theory for large masses in small volumes.

F. You might ask, "So what?" Do we ever have large masses in small volumes, classically?

1. Yes! The singularity in a black hole and the birth of the Universe are obvious examples.

2. Even without these, the incompatibility is deeply troubling and pervasive: All of *empty space* is affected by it!
    - **a.** According to the Heisenberg Uncertainty Principle, as one goes to very small size scales, space-time curvature becomes huge and varies chaotically.
    - **b.** If one extrapolates to zero volume, formally, there are infinite energy fluctuations.
    - **c.** Even stopping at the Planck length (10^{-33} cm), the problems are terrible: One expects the vacuum energy density (cosmological constant), Ω_{Λ},, to be 10^{120}, yet the observed value is 0.73.
    - **d.** If one postulates a perfect cancellation of the quantum fields, with positive fluctuations exactly balancing negative ones (because they "borrow" energy), the vacuum energy density should be precisely 0, yet the measured value is 0.73.
3. Thus, a unification of quantum mechanics and general relativity (i.e., a quantum theory of gravity) is definitely needed.

III. No fully self-consistent theory has emerged, but a large number of theorists are focusing their attention on *string theories* (also known as *superstring theories*).

A. In this mathematically complex theory, the fundamental "point" particles are actually vibrating 1-dimensional (1-D) packages of energy called *strings*.

1. The strings are tiny, on the order of the Planck length (10^{-33} cm).
2. No smaller entities exist, and it makes no sense to talk about smaller scales.
3. Not going to points (zero volume) avoids the infinite-energy quantum fluctuations.
4. Strings are fundamental, indivisible—like letters in a word.

B. The goal of string theory is to explain all physical properties of forces and particles, with no unknowns.

1. The "stuff" of all matter and forces is the same, providing a unifying framework.
2. Different particles correspond to different modes of vibration of strings, like different musical notes of a violin.

C. A problem with string theory is that, currently, none of the observed particle masses has been explained.

1. Typical particles have the Planck mass (10^{19} proton masses).
2. To get down to normal particle masses, many vibrations must cancel out.
    - **a.** The vibrations come in pairs, just like particles in supersymmetry theories—hence, *superstring theories*.
    - **b.** When the cancellation is perfect, one gets gravitons, which have zero mass and carry the gravitational force.

3. Many particles are predicted to exist, but we can't test for them yet because our particle accelerators are not sufficiently powerful.

D. What, then, is so alluring about string theory?

1. It has a great deal of mathematical elegance; it is considered aesthetically pleasing.
2. Certain relationships are so appealing that it seems they "must" be right.
3. There are historical precedents to this. For example, in Einstein's view, GR was almost too beautiful to be wrong.

IV. For the mathematics of string theory to work, there must be at least 10 dimensions!

A. Eleven dimensions is now the favored quantity, in a not yet fully developed extension to string theory called *M theory* (for "membrane," "mystery," "mother of all," and other possibilities).

B. Most of the dimensions are wrapped up on tiny scales, the Planck length.

1. For example, consider a thin garden hose stretched across a yard.
   - **a.** From far away, it looks 1-D, but on the hose, ants can crawl around.
   - **b.** It is 2-D, with one of the dimensions curled up on a small scale.
2. Another example is sandpaper seen from far away: It looks 2-D but is actually 3-D.

C. A historical precedent to the idea of extra dimensions is the Kaluza-Klein theory.

1. In 1919, Theodor Kaluza suggested that there are four (not three) spatial dimensions.
2. He then found that electromagnetism (E&M) theory comes naturally from GR! There may be a deep connection between E&M and GR.
3. In 1926, Oscar Klein refined this idea. He said that the extra dimension is curled up, perhaps on a tiny scale.
4. Though initially intriguing, the Kaluza-Klein theory was soon forgotten, because it seemed to be in conflict with data (e.g., the properties of the electron).
   - **a.** But other forces and particles weren't known yet, and the possibility of yet additional dimensions was not sufficiently tested; the rejection of the theory was premature.
   - **b.** The idea was resuscitated 50 years later, and it has met with more success.

D. Why are only three spatial dimensions not curled up?

1. We don't know. Other choices are certainly possible.

2. We also don't know the shape of the curled-up dimensions. There are thousands of possibilities.
   - **a.** Examples of simple shapes are a loop, a sphere, or a donut.
   - **b.** These extra dimensions exist at every point in our 3-D space, and they "point" or extend into directions we cannot see—they aren't like warts on your arm.
   - **c.** The allowed shapes in string theory are called *Calabi-Yau spaces*. They are generally 6-D or even 7-D spaces.

V. How do we experimentally verify string theory? Do the theories make testable predictions that can be used to discriminate among them?

A. One much-touted "prediction" is the graviton.

1. All variations of string theory generically predict the existence of gravitons.
   - **a.** However, gravitons have not yet been observed.
   - **b.** Moreover, other theories also predict the existence of gravitons; thus, this prediction is not unique to string theory.
2. Supersymmetric partners are predicted—but these, too, are not unique to string theory, and they have not yet been observed.
3. Dark energy provides a potentially great astrophysical test.
   - **a.** Any string theory that categorically denies the possibility of dark energy must be wrong.
   - **b.** Or it must provide an entirely new framework with which to explain the accelerating Universe.

B. Recently, promising ideas from string theory and related theories include a new twist: the possibility of macroscopically big dimensions.

1. Suppose gravity resides mostly in another spatial dimension.
   - **a.** This could help explain its measured weakness.
   - **b.** The other forces (E&M and so on) "feel" or "see" only the three usual spatial dimensions, which is why we have not yet detected that dimension.
   - **c.** The situation is reminiscent of Edwin A. Abbott's book *Flatland* (1884).
2. A potential test involves the collision of high-energy particles in accelerators.
   - **a.** If gravitons are formed and escape to another dimension, there will be an apparent violation of the law of conservation of energy in our dimensions.
   - **b.** This is analogous to heat escaping into space when billiard balls collide: Energy is not conserved in the 2-D plane of the billiards table.
   - **c.** Experiments are currently being conducted to look for this effect.
3. Gravitons produced by a core-collapse supernova might also escape into other dimensions.

        - a. The fewer extra dimensions there are, the more gravitons escape.
        - b. Measurements of SN 1987A rule out 4-D and, possibly, 5-D space.
        - c. The total neutrino energy agreed with the expected energy.
    4. If gravitons escape into other dimensions, the gravitational force will not be proportional to $1/r^2$; the inverse-square law necessitates only three spatial dimensions.
        - a. It would be $1/r$ in a 2-D plane and independent of r in a 1-D line.
        - b. If violations occur, the largest scale is likely to be 0.1–1 mm; larger ones have been ruled out.
        - c. No violations have yet been seen in experiments down to 0.2 mm.

- C. Might the Universe be embedded with other universes in a higher-dimensional space, like bubbles in a room?
    1. Gravity could reside mostly in the hyperspace, "leaking" into our Universe and, thus, appearing to be weak.
    2. Perhaps a force pulling from the "outside" produces the acceleration of the Universe.
    3. The other universes might have different values for the constants of nature.
    4. One can go crazy thinking about such concepts, but it sure is fun!
- D. It is also possible that our Universe bends around in such a way that there are neighboring "sheets" separated by only a short distance along an extra dimension. Perhaps gravity is transmitted through this extra dimension from distant parts of the Universe.

Essential Reading:

Greene, *The Elegant Universe.*

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Weinberg, *Dreams of a Final Theory.*

Supplementary Reading:

Adams and Laughlin, *The Five Ages of the Universe.*

Calle, *Superstrings and Other Things: A Guide to Physics.*

Strings: http://superstringtheory.com.

t'Hooft, *In Search of the Ultimate Building Blocks.*

Questions to Consider:

1. The Planck mass is very large compared with typical masses of known subatomic particles. Compare the Planck mass with the size of some familiar objects. Is it as the mass of a proton, a bacterium, a grain of dust, a baseball, or an elephant? Conversely, the Planck length is exceedingly small. How many Planck lengths is a proton (10^{-13} cm), a marble, and a car?

2. Can you think of additional methods by which the presence of hidden or invisible dimensions might be discerned?

Lecture Sixteen

Our Universe, One of Many?

Scope: The standard Big Bang theory is very successful at explaining many of the observed aspects of the Universe. However, it has no natural explanation for the geometrical flatness of the Universe, its extreme uniformity, and several other properties. These problems are solved with a popular modification to the standard theory, known as *inflation*. In its first brief moments of existence, the Universe may have experienced an epoch of accelerated, exponential expansion, becoming arbitrarily large because of the effects of dark energy that is reminiscent of the cosmic antigravity driving the currently accelerating Universe. The lecture also mentions alternatives to inflation and other interesting new ideas, although there is little support for them at the present time. Returning to inflation, we discuss how the theory suggests that there might be a multitude of universes physically disconnected from our Universe, possibly having different laws or at least different values for the physical constants. If so, we may live in one of the few universes that developed complexity and life; it happened to have suitable properties just by chance. Universes in which the various constants are modified just a small amount would differ in significant ways, with dire consequences for life as we know it. Universes might also give rise to other universes through black holes. These ideas, though highly speculative, may someday be testable.

Outline

I. The standard Big Bang theory of the Universe has a number of stunning successes

- **A.** It is consistent (almost by design) with the expansion of the Universe.
- **B.** It predicts that there should be a definite maximum age of all objects.
  - **1.** In fact, we've found no stars older than about 13 billion years.
  - **2.** This is consistent with the derived expansion age, 13.7 billion years.
- **C.** It predicts that the Universe should now be bathed in a sea of photons left over from the hot, dense beginning. This is the observed CMBR.
- **D.** It predicts that there should be signs of galactic evolution.
  - **1.** Indeed, we see that most galaxies were born long ago.
  - **2.** Their average properties do change with time.
- **E.** It predicts that there should be a uniform distribution of light elements (produced during the first few minutes after the Big Bang) and a more patchy distribution of heavy elements (produced in stars), as observed.

II. There are also some problems with the theory. Here are two:

- **A.** The CMBR is incredibly uniform, aside from the tiny fluctuations from which clusters of galaxies were born. How did it become this way?
- **B.** The Universe is essentially flat on large scales: $\Omega(\text{total}) = 1.0$, as shown by the CMBR measurements. In the standard Big Bang theory, the Universe rapidly deviates from flatness, unless it was born exactly flat, but this is unlikely to happen by chance.
- **C.** In 1980, Alan Guth and (independently) Andrei Linde proposed a solution: *inflation*, a modification to the Big Bang theory that affects the first tiny fraction of a second.
  - **1.** The Universe began much smaller than suggested by an extrapolation of the standard Big Bang equations backward in time.
  - **2.** It expanded exponentially by an incredibly large factor in a tiny instant of time, perhaps as short as 10^{-35} seconds.
  - **3.** The tiny initial Universe achieved great uniformity through numerous collisions between particles and photons, and it maintained this condition as it inflated.
  - **4.** All initial curvature would have been flattened out by inflation. The Universe became so large that the region we can see (about 14 billion light years in radius) is a tiny fraction that appears flat, just as the Earth's surface appears flat when viewed over small distances.
  - **5.** Following the end of inflation, the Universe would have continued expanding in a manner consistent with the standard Big Bang theory. In a sense, inflation is what *launched* the Big Bang, like throwing an apple.
- **D.** The inflationary epoch of the early Universe may have been propelled by dark energy associated with a state of unbroken symmetry, such as two unified forces that had not broken apart when the temperature of the Universe fell below some critical value. This is a form of quintessence. Similar principles may apply to the *current* accelerated expansion, as discussed in Lecture Fourteen.
- **E.** During the exponential expansion, space stretches faster than the speed of light.
  - **1.** This is *not* a violation of Einstein's special theory of relativity, because it says that no material object can travel *through* space at a speed exceeding that of light.
  - **2.** Put another way, relativity forbids information from traveling through space faster than *c*. But the stretching of space itself cannot be used to transmit information.

III. Although inflation and Big Bang theory are very successful, it is important to consider potential alternatives and keep an open mind.

- **A.** One idea is Paul Steinhardt's *cyclic universe*.
  - **1.** In a 2-D analogy, the Universe is like an infinite plane that collided with another infinite plane, causing it to heat up and expand.
  - **2.** In the future, it will hit other planes, experiencing a rebirth.
  - **3.** This hypothesis is not compelling right now, because it presupposes the existence of smooth infinite planes—something that inflation produces naturally.
- **B.** Another possibility is that the speed of light is variable, as proposed by Joao Magueijo.
  - **1.** If light traveled much faster in the past, some of the problems with the standard Big Bang theory (such as the uniformity in temperature) could be overcome, and perhaps, the current "acceleration" of the Universe would be explained away, too.
  - **2.** Possible evidence has been found for a changing fine-structure constant.
    - **a.** The fine-structure constant is given by $\alpha = e^2/(hc/2\pi)$. It is a measure of the strength of electromagnetic interactions in atoms.
    - **b.** If α is changing, there might be changes in the charge of the electron (e), Planck's constant (h), or the speed of light (c).
    - **c.** However, the claimed changes in α are too small to disprove the accelerating Universe and too large for consistency with existing theories.
    - **d.** The measurements are very difficult to make, and the result is still suspect.
- **C.** A possible alternative to GR is MOND (Modified Newtonian Dynamics), proposed by Mordehai Milgrom.
  - **1.** It applies at accelerations below 10^{-8} cm/s^2 (compared with about 1000 cm/s^2 at Earth's surface): The inverse-square law of gravity is modified.
  - **2.** It can nominally explain the rotation curves of spiral galaxies.
  - **3.** However, it has great difficulties explaining the uniformly hot gas in clusters of galaxies and some other observations.
  - **4.** Moreover, it is not a complete theory, and it violates aspects of GR for which there is good evidence.

IV. Let us now consider the possibility of having multiple universes.

- **A.** Inflation predicts a truly enormous universe having the same physical properties throughout.
  - **1.** Most parts of the Universe are so far away that we can never contact them; thus, they can be considered almost like separate universes.
  - **2.** In many specific models of inflation, the ratio of the *entire* Universe (radius) to the *observable* part of the Universe exceeds the ratio (about 10^{41}) of the *observable* part of the Universe to a *proton*!
  - **3.** The entire Universe could even be a googol (10^{100}) or more times larger than the parts we can see. Its size might even be infinite or essentially infinite.
    - **a.** If there is only a finite number of ways in which a given number of particles can assemble themselves and interact, then it is possible that there are copies of us elsewhere, going through exactly the same thoughts and motions!
    - **b.** Max Tegmark has discussed this provocative idea in detail.
- **B.** Inflation also suggests the presence of physically disconnected universes, possibly with different values for the physical constants or even the physical laws.
  - **1.** There may be regions of different broken symmetry in an inflating universe, just as a heated magnet cools to form magnetic domains pointing in different directions.
  - **2.** Or an inflating region (domain) produces new, distinct, inflating domains within it, as a result of quantum fluctuations.
    - **a.** These inflating regions will subsequently spawn domains that continue to inflate, even as symmetry is broken throughout most of the volume. The process never ends.
    - **b.** This idea is known as *eternal inflation*.
- **C.** Distinct quantum fluctuations arisen out of "nothing" can also produce multiple universes. This "nothing" might be the vacuum of our Universe or the "nothing" outside our Universe.
- **D.** Yet another idea is that a new universe can sprout from within any black hole in our Universe.
- **E.** How can we test for the presence of other universes?
  - **1.** Generally, there is no known way to contact other universes and perform experiments on them, even in principle.
  - **2.** Perhaps light signals could be sent through a *wormhole* (similar to a tunnel).
    - **a.** A future generation might discover matter with antigravity properties (on small scales) and transport it into the wormhole, thereby keeping it open.
    - **b.** Wormholes could also be used to quickly travel to distant parts of our Universe.

V. The physical possibility of multiple universes having different physical properties might explain why our Universe seems so "special."

A. The values of the physical constants (not to mention the laws of physics) seem to be spectacularly "fine-tuned" for life—indeed, almost tailor-made for humans.

B. In many cases, if things were altered just a tiny amount, the results would be disastrous for life and even for the production of heavy elements or molecules. The Universe would be "stillborn" in terms of its complexity. Here are a few examples:

1. If the strong nuclear force were 20% weaker or if the mass of the neutron were slightly higher, there would be only H. The rich periodic table would be nonexistent.
2. If the strong force were 2% stronger or if the weak force were a little stronger, there would be no H. Without H, there would be no water or hydrocarbons.
3. If gravity were considerably stronger relative to electric forces, stars would be more massive, and they would burn out too quickly for life to develop.
4. If the cosmological constant were somewhat larger early in the Universe, stars would not have formed.

C. One can argue that there is an ensemble of universes, perhaps even infinitely many, that span a very wide range of properties (values of the physical constants, particle masses, and so on). We, of course, live in a Universe that allowed life and sentient beings to develop. Such universes might be exceedingly rare.

D. This is a form of *anthropic* reasoning: Things are the way they are, because otherwise, we would not be around to see them.

E. Ancient Greek philosophers could have used such reasoning when contemplating the origin and properties of Earth.

1. There is no fundamental reason that the Earth must have had properties conducive to the formation of life.
2. One concludes that there is an ensemble of planets having a wide range of properties, in many or most cases, not hospitable.

F. To make our Universe a common (typical) one, Lee Smolin has suggested the very speculative notion of *universe heredity*.

1. He postulates that baby universes are born from the singularities of black holes in parent universes.
2. *If* the main characteristics of the parent universe are transferred to its progeny with small mutations and *if* the formation of life is maximized in universes that tend to produce many black holes, then typical universes will support life, and our Universe is not special.

VI. These are truly the frontiers. Who knows where they will take us? Meanwhile, you can get updates on the Web. Here are some useful sites:

A. astroalex.com (has links to other sites).

B. astrosociety.org (the Astronomical Society of the Pacific).

C. hubblesite.org (Hubble Space Telescope news).

D. aantwrp.gsfc.nasa.gov/apod/ (a new astronomical photo each day).

E. space.com (has lot of current information).

F. You might also want to participate in the search for extraterrestrial intelligence by downloading a free screen saver from seti.berkeley.edu—there is a tiny chance that *your* computer will be the first one to detect a real signal!

G. Our understanding of the Universe, though incomplete, is impressive.

1. We have incredible brains and amazing creativity.
2. We seem to be the only creatures on Earth able to figure out how nature works.
3. The fact that we have curiosity and can comprehend the Universe through careful observations, experiments, and deep thought is a gift that we should not squander.

H. The late Richard Feynman stated our position well in a poem. He talks about how life arose from the ocean, how self-replicating molecules eventually formed and became ever more complex, finally moving from the sea to dry land and culminating with conscious, curious humans: "I, a universe of atoms, an atom in the Universe."

Essential Reading:

Guth, *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Rees, *Before the Beginning: Our Universe and Others*.

The Once and Future Cosmos (special edition of *Scientific American*, 2002).

Supplementary Reading:

Linde, in *The Origin and Evolution of the Universe*.

Magueijo, *Faster than the Speed of Light: The Story of Scientific Speculation*.

Smolin, *The Life of the Cosmos*.

Tegmark, *Parallel Universes*.

Questions to Consider:

1. Suppose that during inflation, the size-doubling timescale was only 10^{-38} sec. If inflation started at $t = 10^{-37}$ sec and continued until $t = 10^{-35}$ sec, show that about 1000 doublings occurred. If the Universe started out with a diameter of 10^{-33} cm (the Planck length) at $t = 10^{-38}$ sec, what will its diameter be at the end of inflation?
2. How do you feel about the possibility that there are exact duplicates of ourselves elsewhere, leading exactly the same lives or lives that begin to differ with each passing second of time?

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Web Sites

Adaptive Optics: http://cfao.ucolick.org/. All kinds of information on this technique for eliminating the effects of the Earth's atmosphere.

Anglo-Australian Observatory: http://www.aao.gov.au/images/index.html. Many beautiful photos.

Astronomical Image Library: http://www.syz.com/images. Looking for a picture of a celestial object? Search the database here to find it across the Internet.

Astronomical Society of the Pacific: http://astrosociety.org. Has a catalog of items you can purchase, a nontechnical magazine (*Mercury*), and other items of interest.

Astronomy: http://www.astronomy.com. One of the leading magazines for the general public.

"Astronomy Café": http://www.astronomycafe.net/. Astronomer Sten Odenwald answers questions sent to him. The query that's been bugging you is probably already answered among the posted replies.

Astronomy Picture of the Day: antwrp.gsfc.nasa.gov/apod/. A new astronomical photo each day, with a description.

Astrophotography: http://www.astropix.com/, http://home.arcor-online.de/axel.mellinger/, http://www.ne.jp/asahi/stellar/scenes/english/, http://www.3towers.com, http://www.scienceandart.com. These and many other sites have some gorgeous astrophotos.

Bahcall, J.: http://www.sns.ias.edu/~jnb/. A good source of information on solar neutrinos (look at the link for "popular accounts").

Berkeley Astronomy Department: http://astron.berkeley.edu. University of California, Berkeley.

Chandra X-ray Observatory: http://chandra.harvard.edu/photo. Images from the world's best X-ray telescope.

Eclipses: http://sunearth.gsfc.nasa.gov/eclipse/eclipse.html. Lots of good information about eclipses, with links to other sites.

European Southern Observatory: http://www.eso.org/. Europe's premiere ground-based observatory.

Extrasolar planets: http://www.exoplanets.org. A frequently updated list, with other information.

Filippenko, A.: http://www.astroalex.com. Has links to other sites.

Galileo spacecraft: http://galileo.jpl.nasa.gov. From here, one can also browse to other NASA/JPL sites.

Gravity waves: http://lisa.jpl.nasa.gov. Has information on the detection of gravity waves.

Hubble Space Telescope: http://hubblesite.org/newscenter/. Much information on the telescope and almost all areas of astronomy.

Keck Observatory: http://www2.keck.hawaii.edu/. The largest optical telescopes in the world.

NASA Goddard Space Flight Center: http://www.gsfc.nasa.gov/. Has results from many missions; check /topstory for headline news.

NASA's Planetary Photojournal: http://www-pdsimage.jpl.nasa.gov/PIA/PIA.html. Designed to provide easy access to the publicly released images from various Solar System exploration programs. See also *Welcome to the Planets* at http://pds.jpl.nasa.gov/planets/.

National Optical Astronomy Observatories: http://www.noao.edu/image_gallery. Lots of nice photos.

Nine Planets: http://www.seds.org/nineplanets/nineplanets/. This "multimedia tour of the Solar System" is "an overview of the history, mythology, and current scientific knowledge of each of the planets and moons in our Solar System."

Parviainen, P.: http://www.polarimage.fi. Has many gorgeous photographs of atmospheric phenomena, auroras, and celestial phenomena.

Powers of 10: http://www.powersof10.com/. Great for an overview of different size scales.

Satellites: http://www.heavens-above.com. Information on where things are in the sky, for any desired location on Earth.

SETI screensaver: http://seti.berkeley.edu. Download the free software and help with the search for extraterrestrial intelligence!

Sky & Telescope: http://www.skyandtelescope.com. One of the leading magazines for the lay pubic.

Space.com: http://space.com. Lots of news about space discoveries and other information.

Strings: http://superstringtheory.com. The official string (superstring) theory web site.

Supernovae: http://www-cfa.harvard.edu/oir/Research/supernova/SNlinks.html. Many useful links to supernova web sites.

Wilkinson Microwave Anisotropy Probe web: http://map.gsfc.nasa.gov. Has much information on the WMAP, microwave background radiation, and cosmology.

Young, A. T.: http://mintaka.sdsu.edu/GF. Has excellent explanations of mirages, the green flash, crepuscular rays, and other atmospheric phenomena. (He also has links to many other useful sites.)